Effect of Formation Damage on Horizontal Well Performance

by

Syed Sajid Hasan

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

PETROLEUM ENGINEERING

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DEANSHIP OF GRADUATE STUDIES

This thesis, written by **Mr. Syed Sajid Hasan** under the direction of his Thesis Advisor and approved by his Thesis Committee, has been presented to and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE** in **Petroleum Engineering**.

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ACKNOWLEDGEMENTS

I wish to express my deep gratitude and thanks to Dr. AbdulAziz Al-Majid. Chairman of the thesis committee, for providing assistance and valuable guidelines throughout the thesis work. I also esteem the support extended by Dr. Khalid Al-Fosail. member of my thesis committee.

I greatly treasure the support extended to me by Dr. Habib Menouar. Co-Chairman of my thesis committee. His continuous guidance. incessant patience and understanding helped a long way in concluding my work.

My profound thanks to all the Petroleum engineering faculty and staff of the department, for their cooperation and moral support. I am grateful to ITC department and petroleum engineering computer lab. for providing excellent computing facilities.

Finally I like to thank all my friends at KFUPM. who have extended all the support and made my stay pleasurable.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT (ARABIC)

اسم الطالب : سيد ساجد حسن

موضوع الدراسة : تأثير تأذي (انسداد) التكوين الصخري

على كفاءة الآبار الأفقية

التخصص : هندسة بترول

تاريخ الحصول على الشهادة : مايو ١٩٩٩

هذه الدراسة تقيم مدى تأثير تأذي (انسداد) التكوين الصخري formation damage على كفاءة الآبار الأفقية. فقد طور فيها برنامج حاسب آلي بلغة " FORTRAN ". هذا البرنامج يوضح التفاعل مع تدفق السائل بين المكمن والبئر مع الأخذ في الاعتبار التأثير المشترك لكل من أدائية التدفق الداخلي inflow performance والاحتكاك مع جدار البئر wellbore friction وتأذي التكوين الصخري في الجزء الأفقي من البئر. لذا بالاعتماد على البرنامج تم تقييم تأثير عوامل مهمة على كفاءة الآبار الأفقية. وقد طور البرنامج بحيث يوضح صورة جانبية متغيرة لمدى التأثر في درجات مختلفة من التأذي damage وسمك المكمن و مدى توحد الخواص به وكذلك طول البئر وقطر الجزء المفتوح. وقد كانت النتائج قريبة ومؤيدة للأعمال التي نفذت مسبقاً في هذا المجال.

ABSTRACT

Name of Student	:	Syed Sajid Hasan
Title of the Study	:	EFFECT OF FORMATION DAMAGE ON HORIZONTAL WELL PERFORMANCE
Major Field	:	PETROLEUM ENGINEERING
Date of Degree	:	May 1999

This study evaluates the effect of formation damage on horizontal well performance. A computer model in the FORTRAN language is developed in this study. The model describes the fluid flow interaction between the reservoir and the wellbore, taking into account the combined effect of inflow performance, wellbore friction and formation damage along the horizontal wellbore. Based on the model, the effect of important parameters on the horizontal well performance has been evaluated. These include various skin profiles with different degrees of damage, reservoir height and anisotropy and well length, diameter and open fraction. The results compare favorably with the work available in the literature.

CHAPTER 1

1. INTRODUCTION

Horizontal wells are being utilized throughout the world in an ever increasing fashion. There were estimated 60 successful wells in 1987 around the world. By the year 1996, in North America alone, the number increased to more than 12,300. In Saudi Arabia about 5-10% improvement in recovery factor is expected due to horizontal drilling i.e., close to 12.5 to 25MMbbls of additional recovery [1].

In general the possibility of drilling horizontal wells have been evaluated for:

- Tight reservoirs, especially if vertical fractures are suspected.
- Naturally fractured reservoirs containing vertical fractures.
- Unconventional low permeability gas reservoirs.
- Thin formations.
- Thicker zones of marginal permeability.
- Thin oil columns, when bottom water and/or gas cap is present
- Soft formations such as chalk which are liable to collapse

- Old reservoirs that have no drive mechanisms.

- Producing reservoirs that are extremely high dipping.

- Secondary recovery operations (increased injection area and sweep efficiency).

- Heavy oil reservoirs

- Reduction of turbulence in gas reservoirs.

- Exploration and development of inaccessible locations.

- Areas where environmental concerns minimize number of surface locations.

This has been the most extensive list appeared in the petroleum engineering literature to date [15].

However some of the disadvantages associated with horizontal drilling are high cost, difficulty in logging, stimulation and selective perforation and limited re-completion alternatives for high water or gas rates.

One of the major factors responsible for the poor performance of some of the horizontal wells, is attributed to formation damage. The nature of damage in horizontal wells is not very well understood as compared to vertical wells. Main reasons are greater depth of invasion because of larger exposure times, selective cleanup/damage because of low drawdown applied, difficulty in stimulation jobs and anisotropic nature of damage which might embed some of the staggered perforations etc. These factors get further complicated as the well penetrates zones of highly variable reservoir quality.

Flow profile measurements in certain horizontal wells [2,13,15,16] indicate that the flow contribution along the well is limited to a small fraction of the drilled length thus drastically reducing the effective length of the well. One of the reasons in these cases is the distributive and severe formation damage. This variable nature of the formation damage in horizontal wells adds more difficulty to forecast the production from these wells. In the literature, most researchers assume in general a constant value of the skin along the horizontal section of the well; because the analytical expression of the productivity index cannot accommodates easily a variable skin. This single-valued skin approach is not quite accurate as it contradicts with the real nature of the problem.

A single value of skin has been used historically, because it can be justified in the case of radial flow in a given pay interval, such as the case with vertical wells. In the case of horizontal wells it would be difficult to prove that the permeability reduction would be the same as especially in the case of a very long well reaching 3000 ft or more.

CHAPTER 2

2. OBJECTIVES OF THE STUDY

Horizontal wells are generally successful in enhancing well productivity and reducing conning effects etc. In general, large reservoir contact area with the well is considered as the main factor in achieving the desired objectives from horizontal completion and hence the tendency to achieve larger horizontal well lengths. However on the other side there are factors which tend to reduce the horizontal well productivity and add difficulty in their performance prediction. General permeability impairment near the well bore region, related with drilling induced formation damage and pressure drop along the well, when of the order of the reservoir draw down are the forefront factors in discussion. Effectiveness of perforations and their distribution along the well also play a key role in determining the overall well performance.

Formation damage is often modeled using a skin factor 'S' in the Darcy flow equation. In general this skin is assumed to be a constant, despite the expected conic shaped damaged zone along the horizontal well length. This damage attributed to mud invasion, has the largest base towards the heel, reflecting that damage is more severe near the heel compared to the area close to the toe. The single value of skin used, if not measured directly from the well test analysis, can be based on laboratory regained permeability tests conducted on core samples. Field experience has shown that these methods give oversimplified value of the skin factor 'S' and there has been no thorough assessment of the error due to this simplification in the literature.

The objective of this study is to develop a computer model that conglomerate various individual horizontal well performances to give overall horizontal well performance. These include distribution of perforated intervals, variable skin distribution along the well and effect of frictional forces etc. The model thus describes the fluid flow between reservoir and the wellbore, taking into account, the distributive skin effect and its interaction with frictional gradient along the well length, on the inflow performance. A parametric study is planned to see the influence of critical parameters on the well performance.

CHAPTER 3

3. LITERATURE REVIEW

A literature survey is provided in this chapter. The goal is to present briefly, the published literature related with the following topics;

a) Productivity models of partially completed horizontal wells.

b) Effect of variable natured formation damage on the productivity impairment of horizontal well, and

c) Role of frictional forces on the flow behavior of horizontal wells.

3.1 FORMATION DAMAGE IN HORIZONTAL WELLS; ANALYTICAL TREATMENT

This part of the literature survey reviews the efforts in the published materials about characterizing formation damage in horizontal wells. The emphasis is on both analytical expressions, and laboratory studies that has been used to describe the real and variable nature of the formation damage as it occur along the horizontal wellbore.

The skin concept with vertical wells is often used to measure the degree of success in these completions. Skin is also used to measure and monitor formation damage over time by subsequent pressure transient tests. The skin factor and the productivity index are generally, considered to be the central parameters in procedures of well diagnosis and surveillance.

With horizontal wells the damage may occur over the entire pay interval. or may occur in discrete intervals in varying degrees, depending on drilling conditions and change in lithology along the well bore. The resultant inflow may occur over one or more short segments rather than the entire horizontal wellbore. This limited drainage profile can lead to premature coning, and poorer than the expected performance.

3.1.1 Skin Concept by Van Everdingen and William Hurst [1953]

Van Everdingen [3] and Hurst [4] introduced the idea of a skin factor to the petroleum industry in 1953. They characterized this skin effect by an additional pressure drop across the damaged zone. The skin pressure drop was given by:

$$(\Delta p)_{skin} = S(\frac{141.2B\mu}{k})(\frac{q}{h}) \tag{3-1}$$

Commonly, the skin factors in vertical wells can very from +1 to +10, and even higher values are possible.

3.1.2 Hawkin's Improvement [1953]

Hawkins [5] in 1956 overcame the problem of negative skin in equ.3-1, by defining a concept thick skin. He showed that the skin factor for a skin zone of radius r_s with permeability k_s in a formation with permeability, k, and wellbore radius, r_w, can be shown to be (see Figure 3-1a):

$$S = [(k / k_s) - 1] \ln(r_s / r_w) \tag{3-2}$$

As shown in Figure 3-1b, because of the presence of this damaged skin zone, the real and ideal flowing bottom hole pressures differ. The difference in pressure is equal to the pressure drop across the skin zone. With this modification positive values of skin are taken to reflect a damaged region around the well bore while negative values represent fractured or stimulated vertical wells.

3.1.3 Work of Sparlin and Hagen [1989]

Sparlin and Hagen [6] and Mauduit [7], have reported the following equations to calculate flow rate from a damaged horizontal well. As shown in Figure 3-2, if d represents thickness of the damaged zone around the horizontal well, then the average vertical permeability, k_{a-v}, and the average horizontal permeability, k_{a-h} are calculated as:

$$k_{a-v} = \frac{k_s k \ln\left[h / (2r_w)\right]}{k \ln\{(r_w + d) / rw) + k_s \ln\left[h / (2r_w + 2d)\right]} \tag{3-3}$$

$$k_{a-h} = \frac{k_s k \ln(r_e / r_w)}{k \ln((r_w + d) / rw) + k_s \ln[r_e / (r_w + d)]} \quad (3\text{-}4)$$

$$\frac{q_d}{q_h} = \frac{\ln(c) + (h / l) \ln[h / (2r_w)]}{(k / k_{a-h}) \ln(c) + (k / k_{a-v})(h / L) \ln[h / (2r_w)]} \quad (3\text{-}5)$$

Where; $c = [r_{eh}+(r^2_{eh}-(L/2)^2)^{0.5}]/[L/2]$; q_d and q_h are damaged and undamaged horizontal well flow rates, respectively.

These calculations are valid only for isotropic reservoirs where reservoir permeability is *k*. The authors calculated (See Table 3-1) the loss in production because of the damage as shown in equ.3-5.

3.1.4 Study by Peterson and Holditch [1990]

Peterson and Holditch [8] conducted a detailed investigation of factors effecting production from the horizontal wells in low-permeability gas reservoirs. They performed sensitivity analysis of most critical parameters like wellbore length, anisotropy, skin damage and drainage area which effect the horizontal well performance; using single-phase, three dimensional reservoir simulator. They showed that skin damage around horizontal well length can severely curtail gas production and the effect is more pronounced when L/X_e ratio is small, $k_s<0.1k$ and when value of anisotropy, $\beta>3$.

The authors however, did not mention the analytical formulation of skin used, to study its effect on horizontal well performance.

3.1.5 Skin Characterization by Joshi [1991]

Joshi [9] mentioned in his book, that in general drilling related damage in a high-permeability reservoir is smaller than that in a low-permeability reservoir. For the similar skin damage value, the influence of damage on horizontal well is not as detrimental as in vertical wells. Thus horizontal well can sustain more damage than vertical wells without a significant loss of well productivity. The author however also realizes, that due to additional drilling time incurred in horizontal wells, they show more near wellbore damage than the vertical well.

The excessive damage, which is related with larger exposure time, results in a conical-shape damage, with larger base at the well heel. See Figure 3.3a. The author also mentioned an expected variable skin profile along the horizontal well length. This is shown in Figure 3.3b.

3.1.6 Horizontal Well Damage Characterization by Frick and Economides [1991]

Frick and Economides [10] in 1991, made the first attempt to develop an expression for skin effect on horizontal wells that takes into account the permeability anisotropy ratio, and the damaged shape is referred to as that of a truncated cone. The skin effect analogous to Hawkin's Equation 3-2, is given by;

$$S_{eq} = (\frac{k}{k_s} - 1)\ln[\frac{1}{(I_{ani} + 1)}\sqrt{\frac{4}{3}(\frac{a^2_{H,\max}}{r_w^2} + \frac{a_{H,\max}}{r_w} + 1)}] \qquad (3\text{-}6)$$

Figure 3-4, describes the shape of damage along the horizontal well and normal to its axis. Permeability anisotropy would generate an elliptic shape normal to the well. The shape of damage depends on the permeability anisotropy index $I_{ani} = \beta$, given by;

$$I_{ani} = \beta = \sqrt{\frac{k_h}{k_v}} \tag{3-7}$$

Simulated responses are shown in fig.3-4, for three different values of I_{ani}. Equ.3-6 confirms the fact that the time of exposure during the drilling and completion would result in a truncated elliptical cone; with the larger base near the vertical section of the well. Equ.3-6 however does not assume damage at the toe end of the well. The R.H.S. of equ.3-6 has to be multiplied by the 'anisotropic scaled aspect ratio (hI_{ani}/L)' before being added to the denominator of the production equations. It is noteworthy, that apart from recognizing a variable nature of damage along the length a single valued skin is presented here, this simplification assumes a constant reduction in the specific productivity index along the well. This is not true, as larger damage at the heel should have larger values of skin.

3.1.7 Renard and Dupuy Analogy of Horizontal Skin [1991]

One of the earliest attempts in defining skin factor in horizontal wells was done by Renard and Dupuy [11] while studying horizontal well flow efficiency. They assumed the following proportionality between horizontal and vertical well skin factors;

$$Sh = (\beta h / L) \times S; \tag{3-8}$$

Where S, is defined in equ.3-2. Hence the pressure drop across the damaged region in case of horizontal well is given by;

$$(\Delta p)_{skin} = S\beta(\frac{141.2B\mu}{k})(\frac{q}{L}) \tag{3-9}$$

The authors concluded that, in general, skin damage was less detrimental to horizontal wells than to vertical ones, due to the longer producing intervals in horizontal wells. However they recognized that severe formation damage could significantly reduce the flow efficiency of horizontal wells. See Figure 3-5.

Equation 3-8, implies that if $\beta h/L<1.0$, then skin damage is less detrimental to horizontal well. In other words as horizontal well length increases or β decreases than horizontal well damage decreases. However this equation does not reflect the fact that the skin damage increases with the length due to longer exposure time.

3.1.8 Gilman's Addition to Renard and Dupuy's Paper [1991]

Gilman [12] pointed out that for similar level of formation damage, horizontal wells will be more affected than the vertical well, even though horizontal well flow efficiency E_h, is greater than the vertical well efficiency E_v..

3.1.9 Economides Addition to Renard and Dupuy's Paper [1991]

M.J.Economides and C.A.Ehlig-Economides [13] in subsequent discussion, pointed out the shortcoming presented in the paper by Renard and Dupuy [11]. They emphasized on using the skin factor as defined by equ.3-6, instead of using S_v, (defined as, S) in the equ.3-8. This discussion provided more realistic approach that has been based on theoretical and practical point of view.

3.1.10 Puncknell and Clifford Total Skin Factor Approach [1991]

Puncknell and Clifford [14] showed that total skin factors can be calculated in wells, which are perforated, damaged, partially completed and deviated. Similarly horizontal wells and the effect of material with in the wellbore (e.g., open hole gravel packs) can also be evaluated. The problem of combining various skin factors is solved by assuming that, close to the well the pressure distribution is unaffected by the well's large scale geometry (i.e., the amount of deviation or partial completion). This total skin factor is given by;

$$S = \frac{h}{h_m} S_{mt} + \frac{h}{h_m} F(S_m + S_a) + S_c$$
$$where,\ F = 1/\sqrt{\cos^2\theta + (k_v/k_h)\sin^2\theta} \qquad (3\text{-}10)$$

This takes into account damage, perforation, anisotropy and partial completion.

3.1.11 Malekzadeh and Djebbar Concept of Effective Horizontal Well Length [1992]

Malekzadeh and Djebbar [15] showed that a damaged horizontal well with a length of X_{f1} is equivalent to a non-damaged horizontal with a length of X_{f2} where:

$$\frac{X_{f2}}{X_{f1}} = e^{-S} \qquad (3\text{-}11)$$

Equ.3-11, shows that for a horizontal well with mechanical skin damage. X_{f2} is smaller than X_{f1} while for a stimulated horizontal well X_{f2} is greater than X_{f1}.

Based on the definition of effective horizontal well length, Malekzadeh et al. [16] applied the concept to horizontal well pressure-drawdown analysis.

3.1.12 Bob Burton Work on Horizontal Well Flow Efficiency [1995]

Bob Burton [17] showed that horizontal wells are less sensitive to formation damage. See Figure 3-6. They based their argument by describing skin factor for horizontal wells, which is analogous to Renard and Dupys's [11] definition. They used 'well flow efficiency' (WFE) to compare the effect of formation damage on well performance.

3.1.13 Engler, Samuel and Djebbar Characterization of Skin [1995]

Engler, Samuel and Djebbar [18] in 1995, presented a model that describes the damaged region around the horizontal well as a combination of cylindrical and conical shape. See Figure 3-7a. Empirical expressions for mud filtrate invasion and drilling penetration rate were used to calculate the maximum damaged radius. They also showed that the skin values calculated at each point along the length, is obtained by taking damaged permeability as a function of damaged radius. See Figure 3-7b.

3.1.14 Study by Toulekima, Mamora and Wattenbarger [1997]

Toulekima, Mamora and Wattenbarger [19], carried out 3-D reservoir simulation studies to evaluate the effect of skin damage, skin location, length of production interval and kv/kh ratio on horizontal well performance.

One of the main conclusion drawn is that productivity is more adversely affected by formation damage near the toe-end than by that near the heel end. Secondly, they concluded that incremental effect of formation damage on oil recovery is more significant for lower skin factors, than for higher skin factors.

3.1.15 Yan and Jiang model for skin variation [1997]

Yan and Jiang [20] formulated a model for invasion depth, from which skin factors at various location based on the damage radius can be calculated. They used skin factor, flow efficiency and production losses based on experimental results and field data to evaluate the extent of formation damage in horizontal wells. How ever they used mean value of skin distribution in calculations.

3.1.16 Ozkan and Raghavan concept of skin [1997]

Ozkan and Raghavan [21] have shown that the conventional perspective of viewing the wellbore damage as an additional pressure drop, is correct only in infinite-conductivity well bores with uniform damage. They showed that the well bore hydraulics in presence of wellbore friction changes the flux distribution (inflow profile) along the wellbore, and thus resulted in additional pressure drops in the reservoir and across the skin zone.

They modeled the skin effect by defining a flux-dependent skin as follows:

$$S_{hm} = \frac{p_f(r_w,x,t) - p_s(r_w,x,t)}{\frac{Lk_r}{hk}[r\frac{\partial p}{\partial r}]_{r=r_w,x}} \tag{3-12}$$

Where;

$$\Delta p_s(r_w,x,t) = \Delta p_s(r_s,x,t) + \frac{141.2\mu}{k_r} q_{hs}(x,t) S_m(x,t) \tag{3-13}$$

This skin pressure drop deviates from the conventional presentation because: the additional pressure drop at skin zone boundary (1st term) is none zero and the mechanical skin factor is a function of flux and is thus time dependent. Thus the authors have introduced a new skin effect concept that rigorously relates the additional pressure drop across the skin zone to the flux distribution.

3.2 FORMATION DAMAGE IN HORIZONTAL WELLS ; LABORATORY STUDIES

Formation damage is a significant problem that has the potential for reducing productivity in horizontal wells in oil and gas reservoirs during almost any type of workover job. Using laboratory results, the effects of various proposed fluids on the petrophysical characteristics of the formation can be examined and weighted prior to the expense and risk of implementing them in the reservoir. Careful and well design laboratory programs can thus reduce costs and increase productivity in many oil and gas reservoirs.

There has been significant number of papers that describe and characterize various mechanisms, which contribute to the formation damage. The authors apart from providing information about such susceptible damage mechanisms; have attempted in various ways to provide answer to the problem. Only some of the key efforts are focused in this part of the literature survey.

3.2.1 Ronald F. Krueger's Study [1986]

Roland F. Krueger in his paper [22] provides a broad overview of the nature of formation damage problems, how they occur during various oil field operations, and their effects on the well productivity. Almost every field operation is a potential source of damage to the well productivity. Step wise he provides diagnosis of formation damage problems, which arise from a particular well operation and then ways and methods to avoid such damage.

3.2.2 Work of Brant, Brent and Douglas [1991]

Brant et al. [23] in their paper provide details on recent advances in laboratory testing and technology which allow almost any type of drilling, completion, workover, or stimulation program to be critically evaluated.

3.2.3 Completion Fluid Design Criteria by A.M.Ezzat [1993]

The author [24] discussed the design criteria and fluid formulations based on laboratory generated data. The paper specifically addresses the reservoirs with different characteristics from Saudi Arabia, where horizontal wells have been successfully drilled

3.2.4 Work of Tim Beatty et al.

Tim Beatty [25] discussed ways of minimizing formation damage by conducting core displacement tests in the laboratory on several core samples. In this way the least damaging drilling fluid can be selected. This paper also outlines core displacement test methodology and presents the results of several core displacement studies. The findings are substantiated with case histories of production data.

3.2.5 Work of Brant et. al. [1994]

This reference [26] provides a mechanistic discussion of various types of formation damage common to horizontal wells; and how they specifically relate to the following formation types:

- Clean and dirty homogeneous sands
- Clean and dirty laminated sands
- Unconsolidated sands
- Fractured sands

- Homogeneous carbonates
- Fractured carbonates and
- Vugular carbonates

The authors also showed various fluid types and procedures, which have experienced success in certain situations. Laboratory testing of drilling fluids on representative cores is highlighted as the main diagnostic tool.

3.2.6 Work of Gruber and Adair [1995]

Recognizing the variable nature of formation damage as it occurs along the horizontal well length, the authors [27] intimate the limitations of laboratory regain permeability tests. The paper presents a more comprehensive laboratory method for evaluation of drilling mud damage and damage removal. Results of tests performed with different muds on several sandstone cores of varying reservoir quality are reported. Finally, implications of these results in predicting horizontal well performance are demonstrated through the use of finite difference modeling.

3.2.7 Study by J.Yan, G.Jiang and F.Wang [1996]

This study [28] relates formation damage and its control for horizontal wells drilled in east China. The authors find that horizontal well productivity is more adversely affected by formation damage than any other parameter. The study also reveals, that production loss in horizontal wells, because of formation damage is more significant than in vertical wells, regardless of the flow efficiency. Further, the authors showed that proper design of drilling fluids leads to successful horizontal wells.

3.2.8 Work of J.C.Shaw and T.Chee [1996]

In this study [29], different commercial drilling fluids are evaluated using similar cores and experimental conditions. Also the effect of various rock types and permeabilities on permeability regain tests are studied. In addition, effect of various drilling mud additives and procedures on the mud removal are also examined.

3.2.9 Work of Hodge et. al. [1996]

In this case study [30] damage induced by drilling fluid is evaluated in the laboratory to assess remedial treatment options. In addition to the laboratory testing, a review of the drilling and completion operations is presented, including the performance of the drilling fluid at high overbalance pressure (around 2600 psi) and the design and execution of subsequent remedial treatments.

3.2.10 Study by Saleh et al. [1997]

Saleh et al. [31] in their paper presented an innovative horizontal wellbore model which is designed to simulate realistic radial flow conditions of horizontal wells in the laboratory. The experimental program evaluates the pre- and post-mud damage well productivity and injectivity. A detailed permeability mapping was presented to show the effect of damage in horizontal wellbore.

3.2.11 Study by Thomas and Sharma [1998]

This paper [32] presents the results of an experimental study on the extent, depth and distribution of mud induced formation damage around a horizontal wellbore. The investigation aimed at assessing the extent of damage in the bottom, middle and upper portions of the heel and toe when a horizontal well is drilled.

3.3 PRODUCTIVITY MODELS TO PREDICT HORIZONTAL WELL PERFORMANCE

In this section of literature, we intend to survey the existing inflow performance for horizontal wells that are partially completed.

3.3.1 Inflow Performance by Goode and Wilkinson [1991]

One of the earlier works in defining the inflow model for partially completed horizontal wells is suggested by Goode and Wilkinson [33].

In this paper a theoretical solution of the inflow pressure in the case of partially perforated horizontal wells is presented. This solution is derived in two ways. Initially the horizontal well is simulated by a set of fractures corresponding to the perforated intervals. These fractures are assumed to penetrate the whole vertical cross-section of the reservoir. Finally a skin factor corresponding to the horizontal well penetration in the vertical direction is used to complete the procedure.

The solution is presented in the form of normalized productivity index *(NPI)* by reference to the openhole solution. The results given in graphical and tabular form for 20% open well, indicates that *NPI* of 0.915 can be achieved for given conditions. Thus partially completed horizontal wells can perform with comparative productivity when compared with openhole wells, especially for thin reservoirs and shorter wells completions. See Figure 3.8. Also the effect of length of the perforated intervals on the normalized productivity index for different reservoir thickness is presented. In general the well flowing pressure is taken as the average pressure existing in the middle of the horizontal section of the well while no pressure drop is assumed, neither a damage skin factor is explored.

3.3.2 Inflow Performance by Pudji Permadi [1993]

In their paper [34] the author, presented a method to estimate the pseudoskin factor for perforated and partially completed horizontal wells, based on the 'Papatzacos' equation. For each open section of partially completed horizontal well, he gave a pseudoskin factor (S_{pt}), that can be accommodated in the given productivity equation. This equation can be normalized with respect to open hole $(S_{pt}=0)$.

During the course of this thesis work, the inflow performance given in this paper was evaluated (not shown here) in detail for different arrangements of open sections. The results indicated that, the *NPI* matches Goode and Wilkinson work only in the case where the perforations are evenly distributed along the horizontal well length.

3.4 PRESSURE DROP ESTIMATION ALONG HORIZONTAL WELL

In this section of our literature we will briefly review the efforts done in the area, without giving details. Various references are mentioned for detailed review.

Single phase horizontal well pressure drop is usually calculated by considering wellbore being represented as horizontal pipe. In practice, a horizontal well will produce, oil, water and gas. To calculate multiphase pressure drop, one still can assume that a horizontal wellbore can be represented as a horizontal pipe. This allows use of several multiphase flow correlation that are available in the literature.

In general, for the same flow conditions, and for the same pipe length, different multiphase correlations may give different values of pressure drop. This problem is quite common even with vertical well correlations. The best approach is probably to measure pressure drop in a wellbore and compare it with various mutiphase correlations to see which correlation gives the best fit of the data. However, it is difficult to insert the pressure transducers at both ends of a horizontal well and calibrate the data. Unless some similar laboratory data are available, it may be advisable to use various 2-phase correlations to estimate wellbore pressure drop and take the average of all results but the highest and lowest values [9].

To investigate a proper correlation that can predict pressure drop along the horizontal well several papers have been reviewed [46-54]. In this study we have used

Beggs and Brill method, which is one of the most commonly used correlation in the petroleum industry [35]. The correlation is applicable for any well bore inclination and flow direction.

3.4.1 The Beggs and Brill Method [1973]

This method [35] is based on the flow regime that would occur if the pipe were horizontal; correlations are then made to account for the change in holdup behavior with inclination.

The Beggs and Brill method uses the general mechanical energy balance equation and the in-situ average density to calculate the pressure gradient and is based on the following parameters:

$$\text{Froud Number} = N_{FR} = \frac{u_m^2}{gD}$$

$$\lambda_l = u_{sl}/u_m$$

$$L1 = 316\lambda_l^{0.302}$$

$$L2 = 0.0009252\lambda_l^{-2.4684}$$

$$L3 = 0.10\lambda_l^{-1.4516}$$

$$L4 = 0.5\lambda_l^{-6.738}$$

The horizontal flow regimes used as correlating parameters in the Beggs-Brill method are segregated, transition, intermittent and distributed. This has been shown in Figure 3.9.

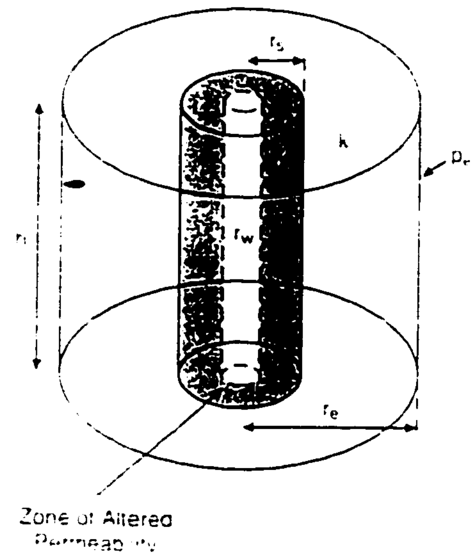

Figure 3-1a: Near wellbore zone with altered permeability [36]

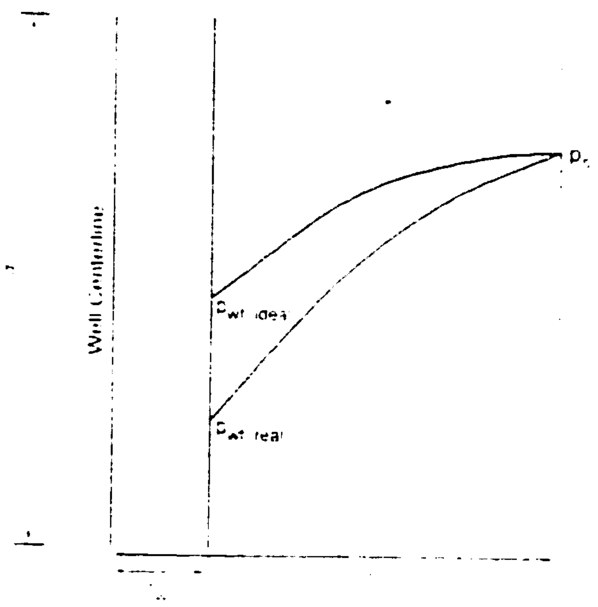

Figure 3-1b: Near wellbore zone showing ideal and real flowing bottomhole pressures [36]

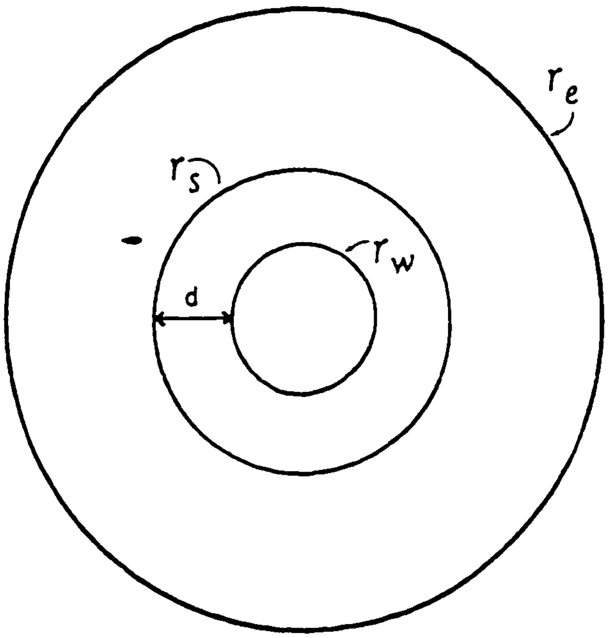

Figure 3.2: A schematic view of a skin zone near wellbore [6]

h = 50 ft, k = 100 md, r_w = 0.33 ft, r_{eh} = 2106 ft, L = 2000 ft				
d, ft	k_s, md	$k_{avg\text{-}vert}$	$k_{avg\text{-}horiz}$	q_d/q_h
0.5	50	82.4	90.5	0.90
1	50	75.6	86.3	0.87
2	50	68.9	81.8	0.82
3	50	65.2	79.1	0.80
0.5	25	61.0	76.0	0.76
1	25	50.9	67.7	0.68
2	25	42.5	59.9	0.59
3	25	38.4	55.8	0.55
0.5	10	34.3	51.4	0.51
1	10	25.7	41.1	0.40
2	10	19.7	33.3	0.32
3	10	17.2	29.6	0.29

Table 3-1: Comparison of q_d/q_h calculations describing the effect of formation damage on horizontal well productivity [6]

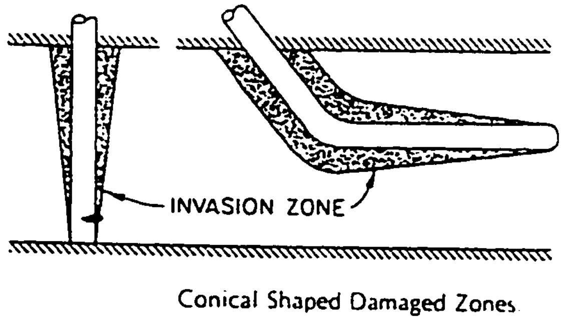

Figure 3-3a: Expected real mud damage zones for horizontal and vertical wells [9]

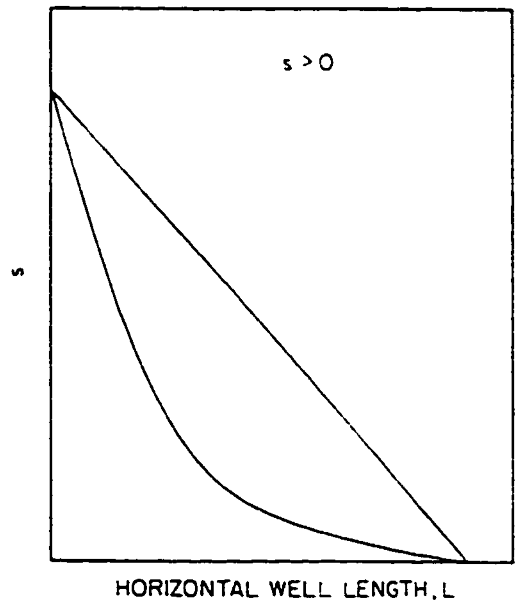

Figure 3-3b: A possible variation in drilling related mechanical skin along the horizontal well length. [9]

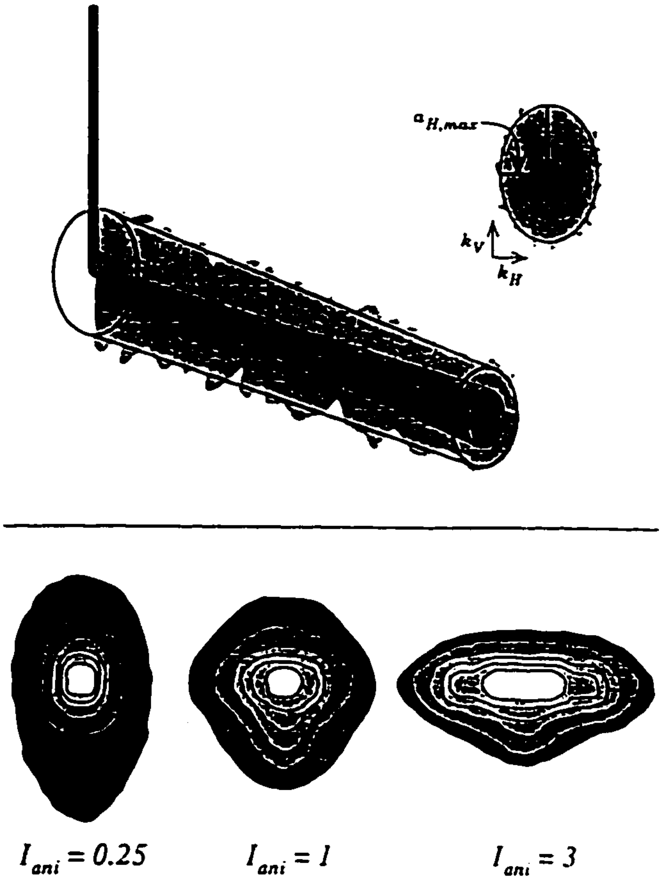

Figure 3-4: Distribution of damage along and normal to a horizontal well. with effect of permeability anisotropy [10]

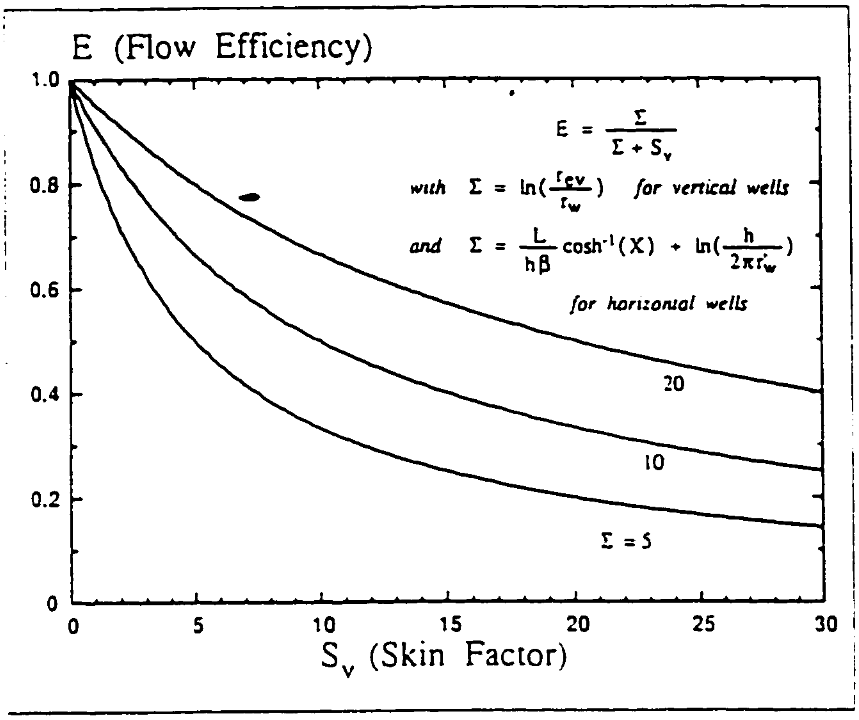

Figure 3-5: Flow efficiency for vertical and horizontal wells. [11]

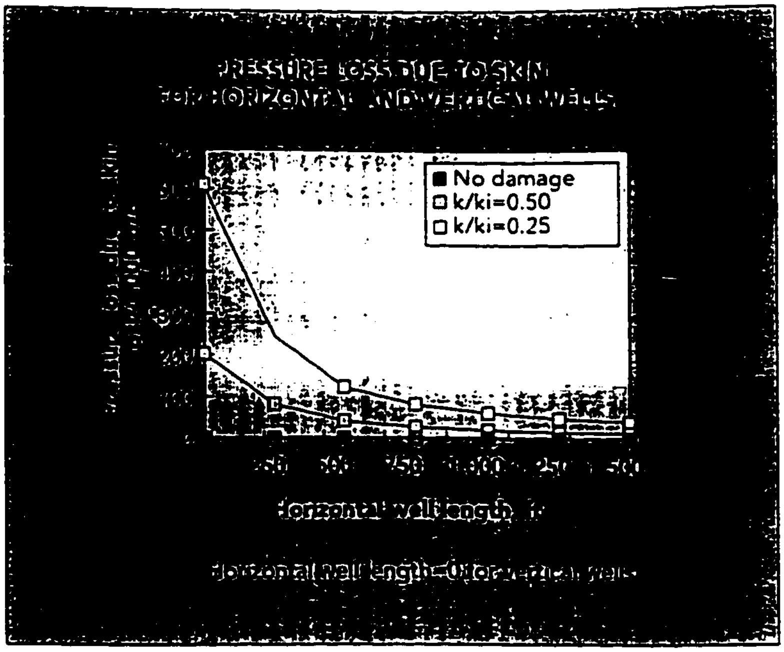

Figure 3-6: Horizontal wells are less sensitive to formation damage than vertical wells. [17]

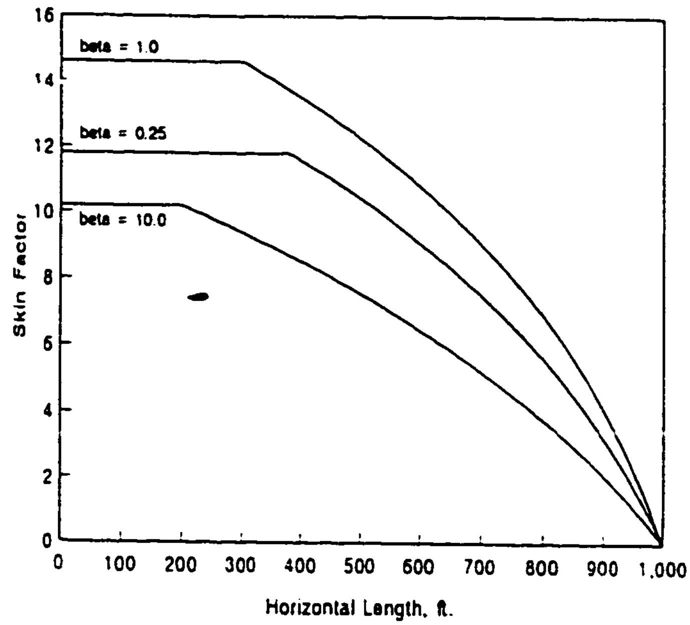

Figure 3-7a: Variation in skin Factor along the horizontal well length [18]

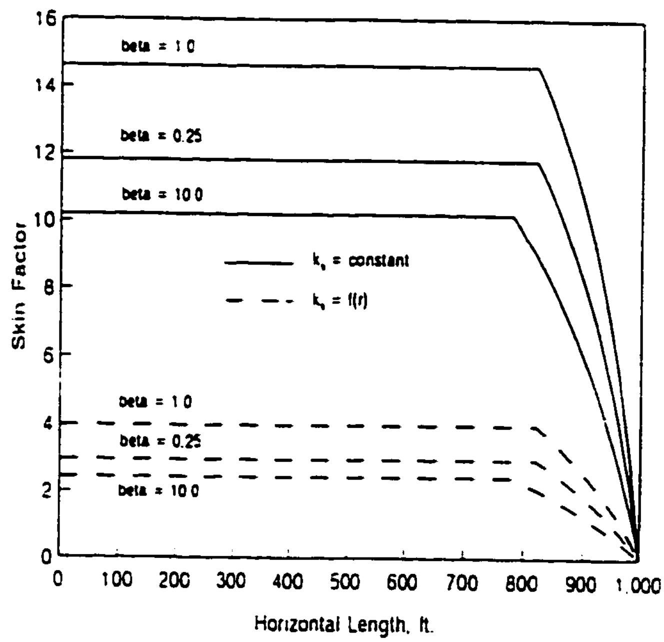

Figure 3-7b: Effect of radial permeability distribution on the variation in skin factor along the horizontal well length. [18]

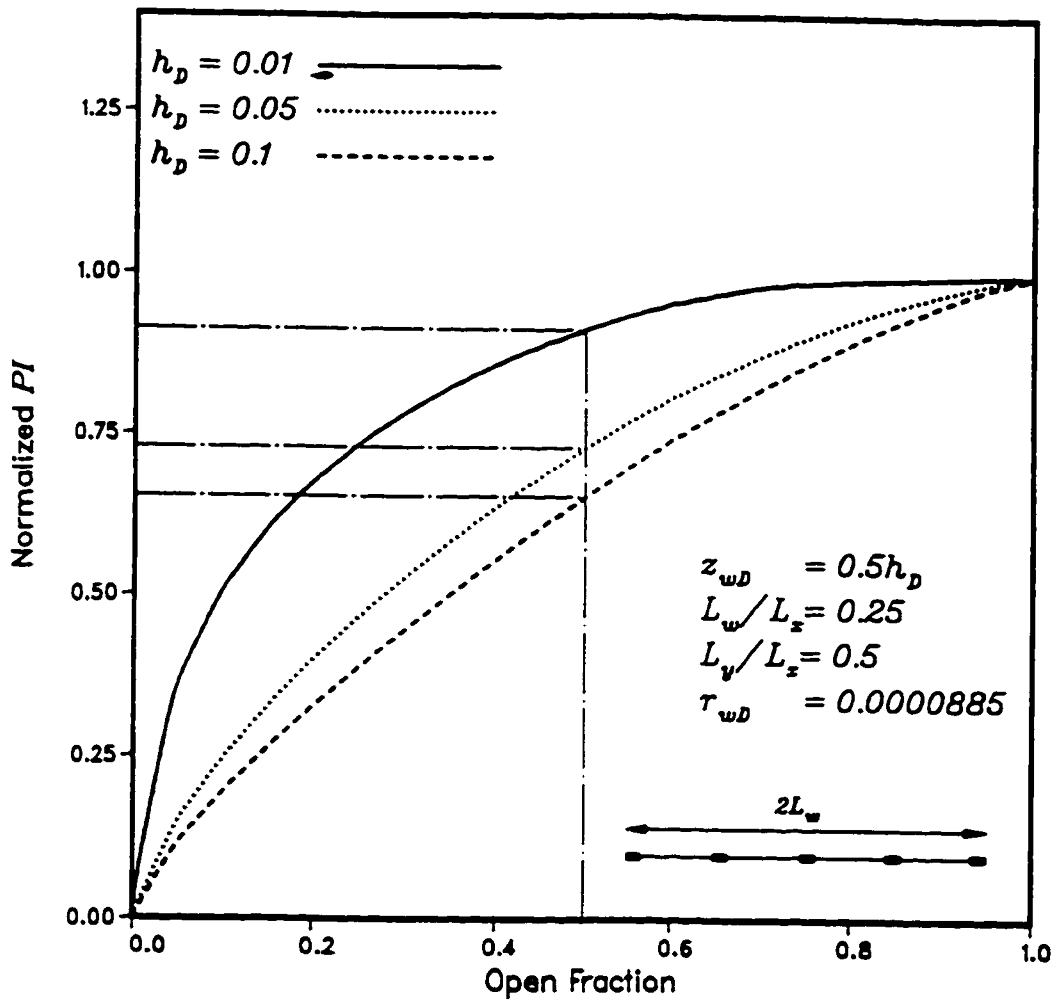

Figure 3-8: Relationship between *NPI* and well open fraction. [33]

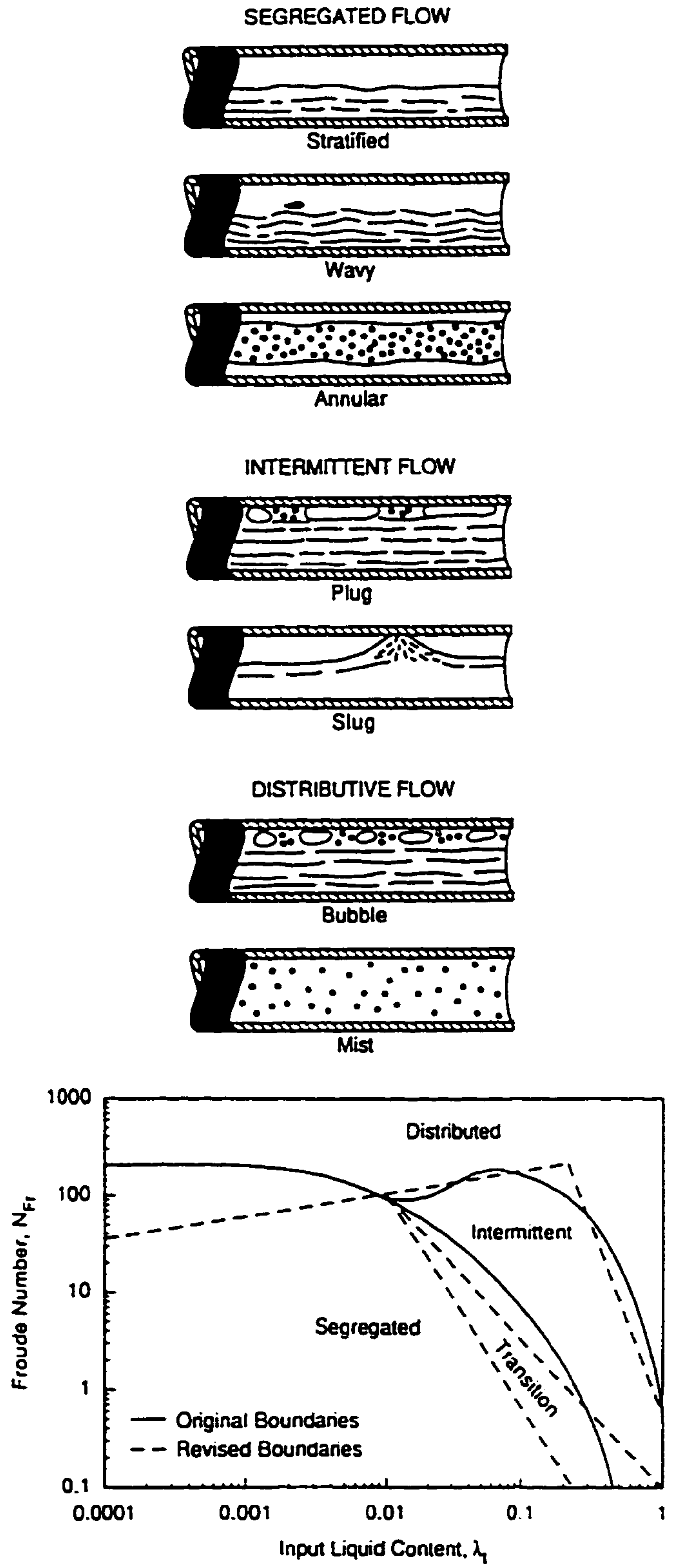

Figure 3-9: Flow regimes in two-phase horizontal flow. [36]

CHAPTER 4

4. FORMATION DAMAGE AND HORIZONTAL WELLS

The issue of formation damage has returned to prominence with the exponential growth of horizontal wells in recent years. The increase in productivity offered by the increased contact between reservoir and wellbore is a two-edged sword. The increased contact area and longer exposure times also allow increased area of damage to form. The relative effect of that damage on production remains unclear. Near wellbore damage impairs the formation ability to conduct hydrocarbons to the well bore. Formation damage lowers well productivity, defers production revenues and is difficult to repair.

4.1 HORIZONTAL WELLS COMPARED WITH VERTICAL WELLS

Formation damage tends to be more significant in horizontal wells than vertical wells for a number of reasons, some of these being [37,38]:

- Longer fluid exposure time to the formation during drilling and greater potential depth of invasion in situations where sustained fluid and solids losses to the formation are apparent.

- Most of the wells remain as open hole or slotted liner completion. Therefor shallow damage, which would normally be perforated through in a typical vertical completion, may remain as an impermeable or low permeability barrier to oil or gas flows.

- Draw dawns applied in many horizontal wells result in selective cleanup of a small portion of the total exposed available flow area, causing the majority of the production from a relatively small fraction of the exposed wellbore face.

- Selective stimulation in wells where slotted liners are in place is impractical. Extensive stimulation of any horizontal section is generally difficult and expensive in comparison to a vertical well, and hence many stimulation programs are inefficient due to cost and/or time limitations.

- The shape of the damage in vertical wells (which drained the reservoir in a uniform planar radial fashion) is generally of cylindrical pattern. However in horizontal wells, (which drained the reservoir in an ellipsoidal pattern) the shape of the invasion pattern will be elliptical in nature, with the direction of the primary axis of invasion ellipsoid being oriented in the direction of highest permeability. Hence for the case of cemented and perforated horizontal wells with staggered pattern of perforations, some perforations (in the high invasion damage direction) might not even pass through the damaged zone and may result in reduced productivity.

- The drill pipe rests on the bottom portion of the hole resulting in cake erosion and less protection for formation damage by the mud cake. This may result in different extent and length of damage in the upper middle and lower sections of the well.

4.2 SOURCES OF FORMATION DAMAGE DURING WELL OPERATIONS

Formation damage can occur whenever non-equilibrium or solid bearing fluids enters a formation, or when equilibria fluids are displaced at extreme velocities. Thus most processes have a potential to cause formation damage. Without going in detail, some of these processes might include [23,25,38]:

1) Drilling
2) Cementing
3) Completion / stimulation
    - Perforating
    - Acidizing
    - Fracturing
4) Workovers
    - Kill fluids

- Hot oil treatments

5) Water flooding or water disposal

6) Enhanced oil recovery processes

    - Miscible flooding
    - Chemical flooding
    - Thermal flooding (in-situ combustion / steam flooding)

7) Excessive injection or production rates

4.3 FORMATION DAMAGE CATEGORIES AND RELATED MECHANISMS

A large number of formation damage mechanisms; arising from the interaction of drilling mud solids and fluids with reservoir solids and fluids can occur. It is always difficult to point out the major damage mechanism actually involved.

Reservoir conditions **core flood tests** on the restored or preserved cores provides a means to simulate the interactions that take place between the invading drilling mud and the formation. This allows measurement of the extent of impairment and visualization of the mechanism. Apart from core flood tests, knowledge of the history of the drilling fluid compositions and **drilling mode** and practices in the area coupled with good **reservoir characterization** is also of critical consideration.

In general formation damage falls into four broad categories upon the mechanism of it's origin, these being [23,26]:

4.3.1 Mechanically induced formation damage

- Fines migration
- Solids Entrainment
- Relative permeability (trapping) effect

4.3.2 Chemically induced Formation damage

- Clay swelling
- Clay deflocculation
- Wax deposition
- Solids precipitation (asphaltenes, sulphur, diamondoids, hydrytes, etc.)
- Incompatible precipitates and scales
- Acid sludges
- Stable emulsions
- Chemical adsorption
- Wettability alteration

4.3.3 Biologically Induced Formation damage

- Bacterial growth
- Bacterial slimes
- Corrosion products due to H_2S from sulphate reducing bacteria(SRB's)

4.3.4 Thermally induced formation damage

- Mineral transformations
- Rock solubility and dissolution phenomena
- Wettability alterations

4.3.5 Other factors

The approach here is not to discuss all these phenomena in detail, however a brief discussion is provided here to alleviate or diagnose specific formation damage problems that are considered in laboratory tests.

4.3.1 MECHANICALLY INDUCED DAMAGE

It has long been accepted that severe permeability impairment can occur when fluid velocities becomes large enough to physically shear and let loose interstitially bound particulates and move them to bridging / blocking locations at pore throat. Wettability alteration can also contribute to this phenomenon. See Figures 4-1 and 4-2.

The injection of fluids containing solids (i.e., unfiltered injection waters or corrosion products from degenerating tubing strings or surface equipment) can also cause gradual plugging and loss of permeability.

Phase trapping can cause severe degradation to relative permeability. For example in Figures 4-3 and 4-4; the reservoir (gas in this case) is initially at *Swi*. The near wellbore region is then invaded by an aqueous based drilling fluid, resulting in a much higher *Swr* (due to capillary trapping phenomena) near the wellbore. It can be seen that effective permeability to gas has been reduced substantially due to the increased trapping of the invaded aqueous phase.

4.3.2 CHEMICALLY INDUCED DAMAGE

The phenomena of clay swelling, upon hydration can often cause severe reductions in formation permeability.

A less understood cause of formation damage, is deflocculation. It occurs when the delicate ionic charge balance (that electrostatically binds clays and particulates together and to pore walls) is disrupted resulting in migration and blockage of clays. This phenomenon generally occurs when a system is subjected to a salinity reduction or 'shock', as shown in Figure 4.5.

Solids and wax precipitation is often a problem in production wells, particularly in miscible flood projects. Other precipitates and scales (e.g., barium or $CaSO_4$) occur due to chemical incompatibility between formation and injected fluids. Many acids also chemically precipitates 'sludges' and 'emulsions' which are entrapped in the near wellbore region. All these phenomena may results in severe, long term permeability impairment.

The injection of various types of chemical additives (surfactants, scavengers, inhibitors, polymers and stabilizers etc.) can result in both wettability changes, which can alter permeability, and also in physical adsorption which can permanently impair permeability. See Figures 4.6a and 4.6b.

4.3.3 BACTERIAL GROWTH

Entrainment of bacteria in injected fluid streams can be a source of severe formation damage and operation problems. Bacterial formation damage can occur both with and without oxygen present. A particular type of bacterial family (sulphate reducing bacteria) has been responsible for the souring of many previously sweet gas reservoirs. H_2S gas generated can be very corrosive and extremely lethal to humans.

4.3.4 THERMALLY INDUCED FORMATION DAMAGE

This type of damage occurs almost exclusively at temperatures exceeding 150°C in hot water, steam flood or in-situ combustion projects. The major source of damage can be attributed to the temperature induced transformation of inert clays, such as kaolinite into swelling smectitic clay, the physical dissolution of portions of the rock matrix and release of encapsulated fines due to high temperature solubility effects and wettability changes associated with steam flooding.

4.3.5 OTHER FACTORS

There are other factors also associated with damage in horizontal wells which are related with rock crushing because of the mechanical action of drill bit and geomechanical stress alterations around well bore. Some of damaging factors in the literature also relates with 'inside wellbore damage', these include deposition of rigid filter cake around well bore, partial removal of cutting or other materials from the wellbore and some times collapsed hole.

The outcome of all this damage is higher pressure drop, for a given production as expected from the analytical solutions.

4.4 POTENTIAL DAMAGE MECHANISM IN DIFFERENT RESERVOIR TYPES

Here we briefly see, whether any analogy exists between formation damage and a particular reservoir type. Ref. [23] is used to address the issue.

Formation damage is extremely reservoir specific and it is impossible to definitively classify or generalize if a particular damage mechanism will be predominant in one reservoir compared to another without laboratory and field qualification. However, extensive lab and field experiments have indicated that certain types of damage are more prevalent in certain reservoir systems than others. This provides a starting point from which to consider the design of drilling, completion and stimulation programs, thereby narrowing the scope of work required and the alternatives which need to be addressed.

Seven broad classification of general reservoir types addressed, are:

1. Clean and dirty homogeneous sands
2. Clean and dirty laminated sands
3. Unconsolidated sands
4. Fractured sands
5. Homogeneous carbonates
6. Fractured carbonates and
7. Vugular carbonates

Table 4-1, classify the different mechanisms and their potential severity for different lithofacies, based on the database of experience for various reservoir types.

4.5 TOTAL SKIN FACTOR

Most of the factors discussed above contribute to the additional pressure drop in the reservoir near the well bore region and are attributed to general permeability impairment. In general a significant contributor to all these factors is drilling operation apart from the other sources as mentioned earlier. This permeability reduction around the well bore is related with skin 'S' and was introduced to the petroleum industry by van

Everdingen and Hurst [3,4] in 1953 to account for differences in observed and calculated bottom hole pressures. This was accomplished in the mathematical models by adding an extra pressure drop at the wellbore, i.e., in a "skin zone" of zero thickness. This dimensionless skin factor for both vertical and horizontal wells respectively are given by:

$$S_v = 7.082 \times 10^{-3} \frac{kh}{q\mu B} (\Delta p)_{skin} \tag{4.1}$$

$$S_h = 7.082 \times 10^{-3} \beta \frac{kL}{q\mu B} (\Delta p)_{skin} \tag{4.2}$$

Although the skin concept was introduced for a specific purpose, it is currently used in a much broader sense. This broader aspect in general cannot be handled by a "thin skin" concept and covers all the different effects that contribute to the additional pressure drop and thus accounts for various corresponding pseudo skin factors.

The total skin factor obtained from the general well tests consists of various pseudo skin factors. Although in isolation, the effect of each of these factors can be accounted, however when occurring together their impact on the measured skin cannot be calculated using published methods [14]. As a result, various workers have suggested that the total skin should be calculated by summing the skins calculated for each factor, as if they act in isolation, i.e.,

$$S = S_1 + S_2 + S_3 + \ldots \tag{4.3}$$

Where *1, 2* and *3* in the subscript etc., account for various pseudo skin factors.

Although this equation is convenient to use it has little validity (unless the individual terms are defined in very special ways). Some authors have already solved part of the problem. For example, the nomograms of Locke and Hong or the more sophisticated approach by Karkas and Tariq [45] can be used to combine the effects of perforation and drilling damage. Several authors [43] have recognized that mechanical skin due to perforation and damage can be combined with partial completion skin if a suitable 'geometric' term is included. Pucknel and Clifford [14] using the work of other authors for particular cases showed how total skin factors can be calculated in wells that are perforated, damaged, partially completed and deviated.

Number of publications in the petroleum literature [14] has identified various pseudo skin factors. The equations presented for evaluation of some of the factors are either numerical or analytical. For some of them no analytical or numerical solution is possible. The contribution of these factors can be obtained by subtracting known pseudo skin factors from the total skin factor. Without elaborating in detail, some of these pseudo skin factors are listed below:

4.5.1 Rate dependent skin

This skin is due to high velocity flows particularly in gas wells where turbulent region near the well is taken as deviation from the Darcy law.

4.5.2 Phase dependent skin

This is associated with phase changes because of the near wellbore pressure gradients. This effect is pronounced in gas condensate reservoirs where condensate accumulates near the well bore region and reduces the gas effective permeability. Also in oil well at pressures less than the bubble point pressure, gas saturation starts to increase, causing a reduction in the effective permeability of the oil even if the gas phase is immobile.

4.5.3 Flux dependent skin

Ozkan and Raghvan [21] introduced the idea that rigorously relates the additional pressure drop across the skin zone to the flux distribution.

4.5.4 Geometric skin

The term 'completion geometric skin' is used to include the effects of partial completion and well deviation and well eccentricity. The method presented by Joshi [39] can be used to calculate the completion geometric skin. Such equation implicitly accounts for the effects of deviation and 'partial completion'.

4.5.5 Anisotropic skin

For deviated and horizontal wells, an 'anisotropic' skin is added if the vertical permeability is less than the horizontal permeability.

4.5.6 Non-anisotropic skin

Materials with in the wellbore radius, such as open hole gravel packs, prepacked screens and filter cakes, creates an additional pressure drop. This is independent of the formation anisotropy [40].

4.5.7 Perforation skin

This accounts for the additional pressure drop that occurs because well is perforated and is not open hole. The perforation skin may further consist of addition of plane flow effect, vertical convergence effect (that may include skin due to crushed zone around the perforation) and well bore effect. Method described by Karakas and Tariq [45] can be used.

Selectively the effect of each of the above pseudo skin factor in the total skin factor is difficult to apprehend. However if overriding factors can be identified than these should be focused before well completion so that decisions, which affect both productivity and cost can be identified. For example geometrical effects, from limited flow entry and well deviation, in many cases play a significant role in the total skin effect. It is important in well diagnosis to separate these effects from effects of changes in near-well properties, when evaluating formation damage. It is often possible, though, to determine the geometrical effect analytically and to remove this part from the total skin value and thus determine the skin effect directly associated with the completed interval. If the skin effects are non-additive, which is often the case, then the process of determining how much of the total skin effect is associated with the completed interval may require a more direct use of analytical models and an iterative procedure.

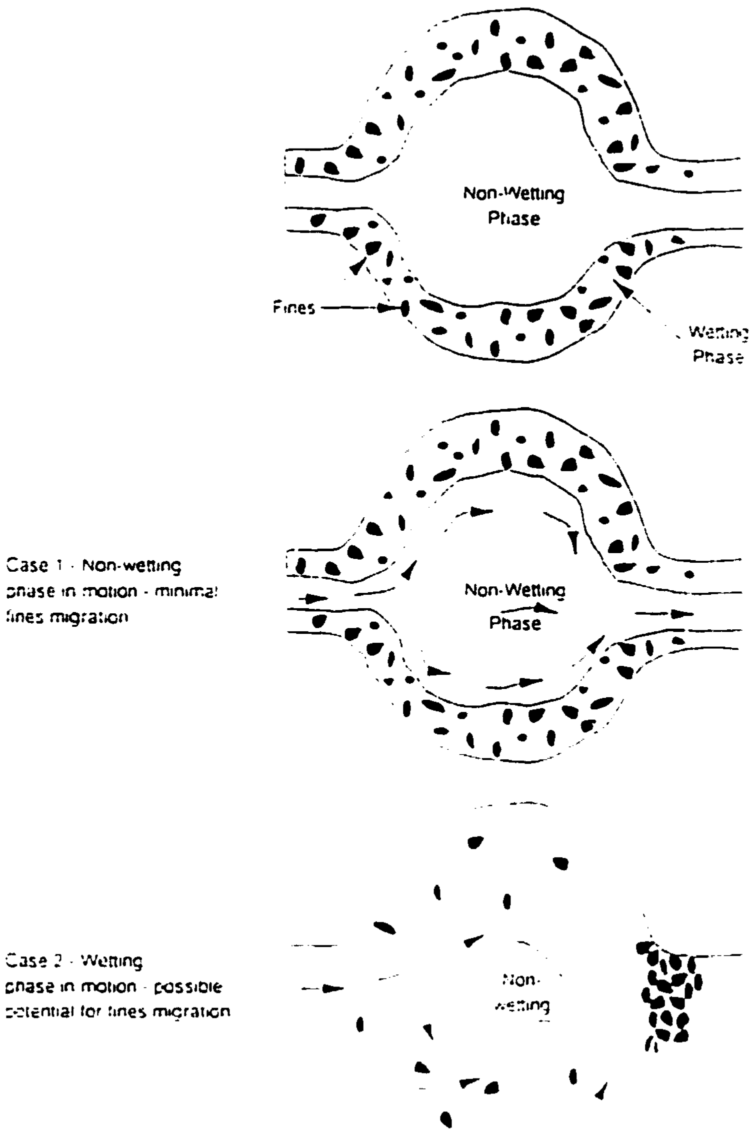

Figure 4-1: Illustration of effects of wettability on fines migration. [26]

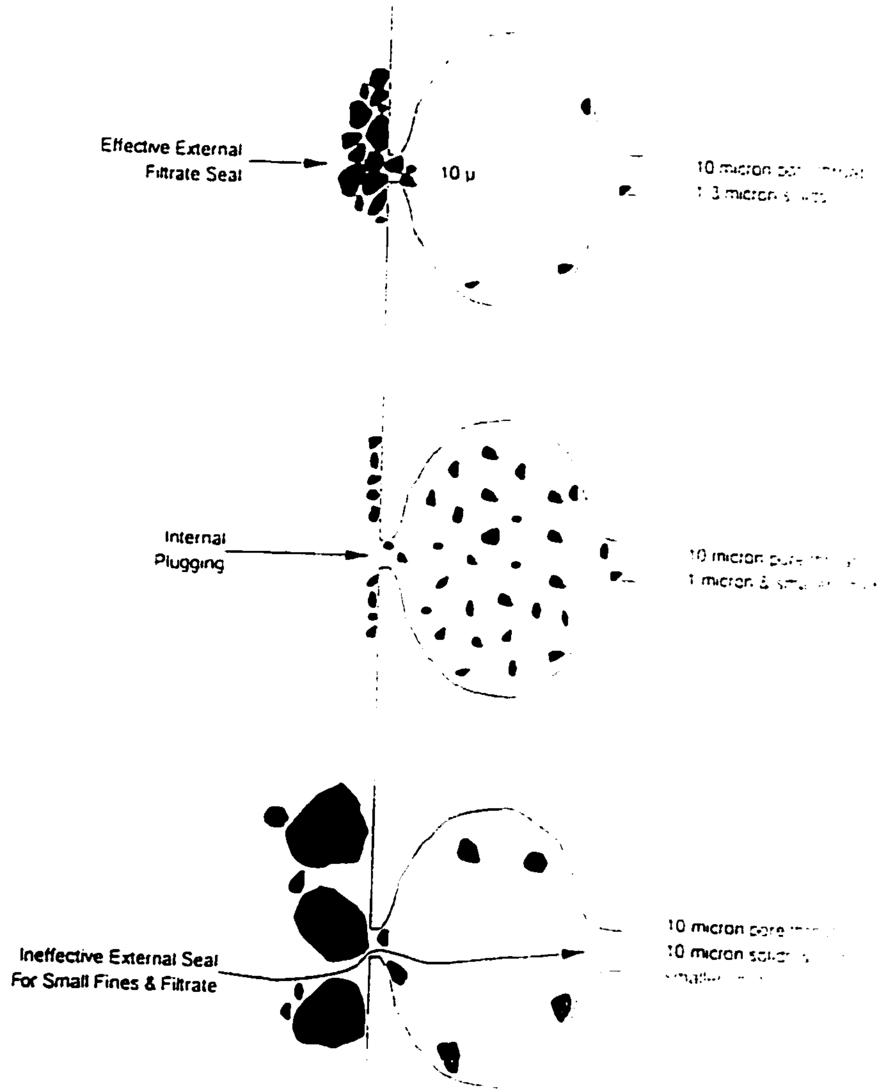

Figure 4-2: Solids invasion into a homogeneous pore system. [26]

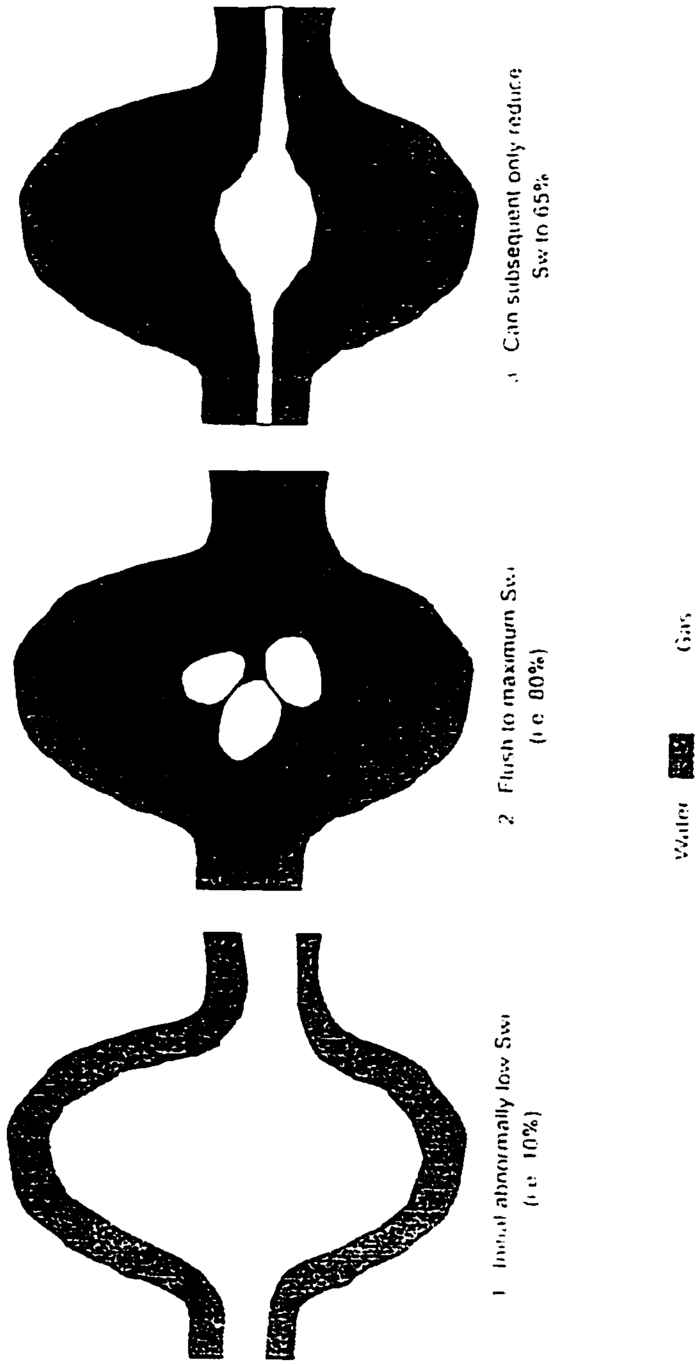

Figure 4-3: Pore scale mechanism of aqueous phase trapping in low *Swi* gas reservoirs. [26]

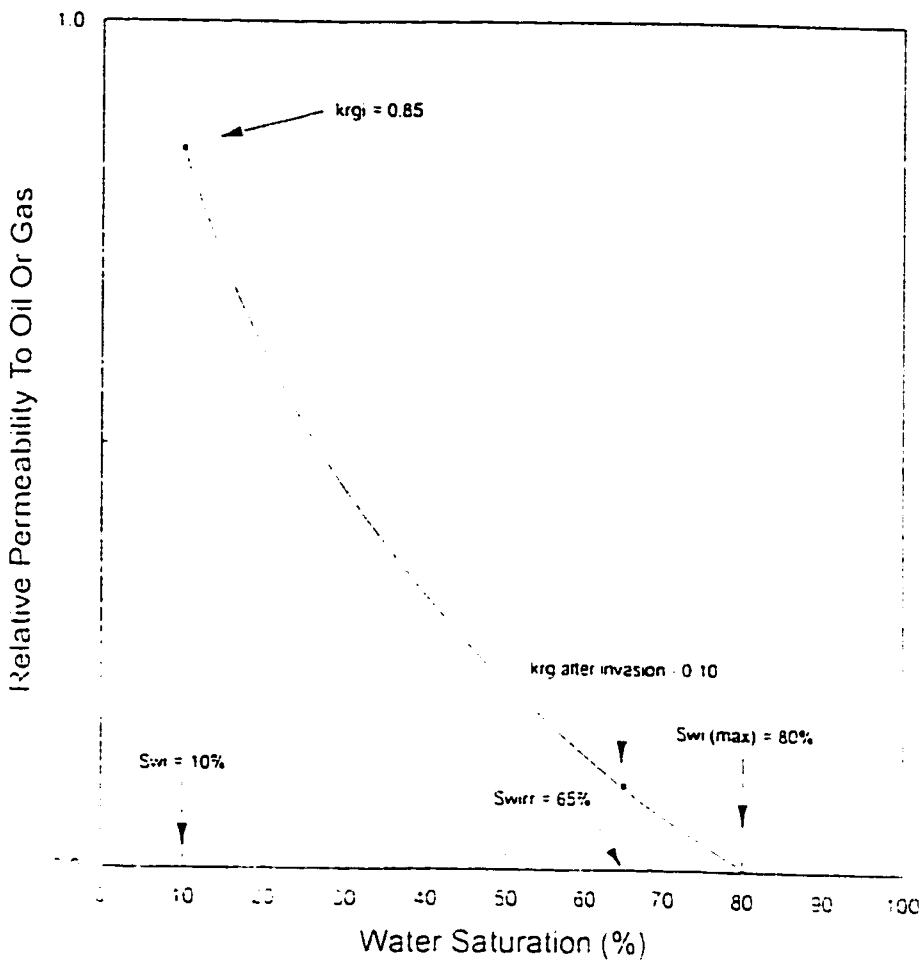

Figure 4-4: Relative permeability representation of a gaseous phase trapping in a low initial *Swi* oil or gas reservoir. [26]

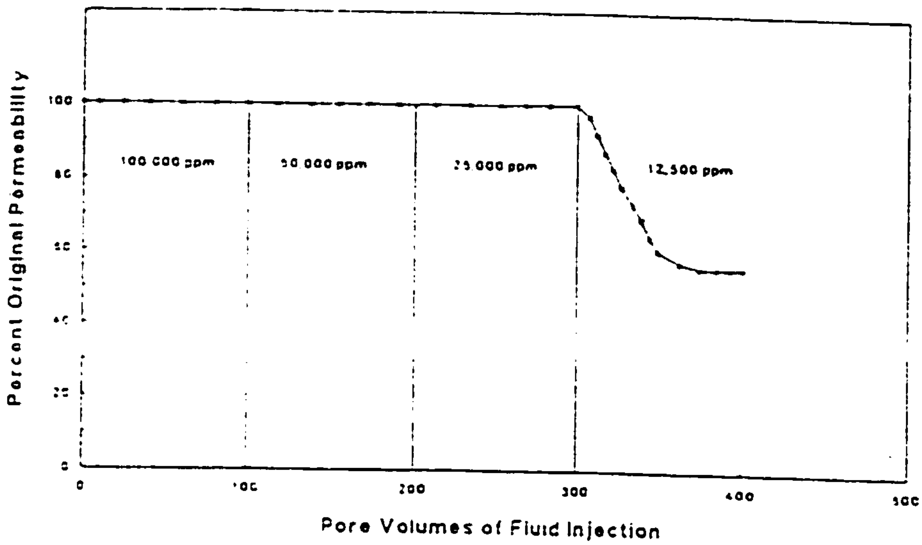

Figure 4-5: Effect of salinity reduction on percentage of original permeability [23]

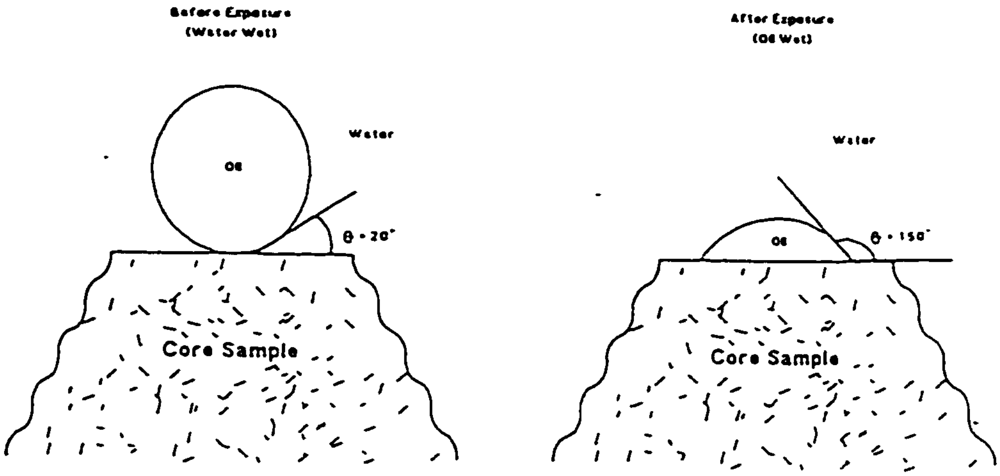

Figure 4.6a: Illustration of wettability determination via contact angle for wettability alteration due to chemical exposure [23]

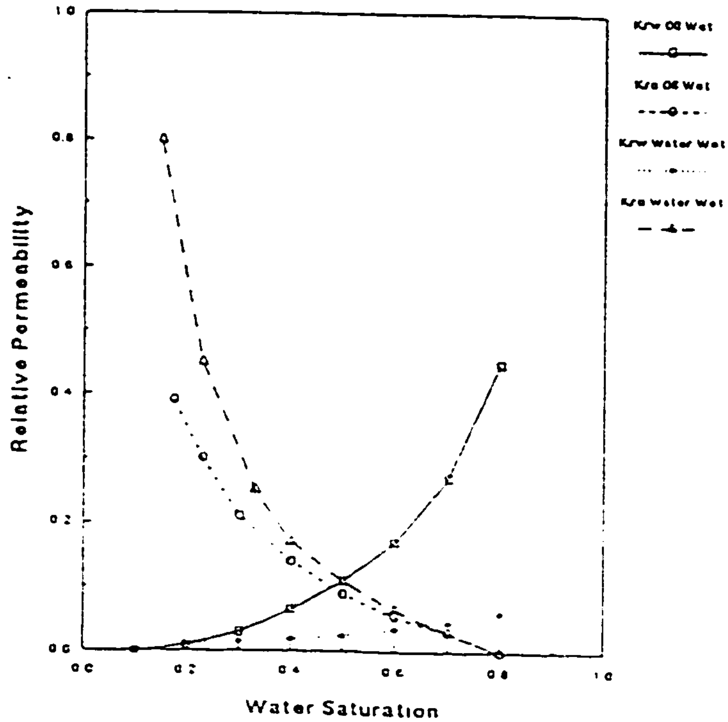

Figure 4.6b: Illustration of wettability alteration effect on oil-water relative permeability curves. [23]

Damage Mechanism	Fluid-Fluid Incompatibility	Rock-Fluid Incompatibility	Solids Invasion	Phase Trapping	Chemical Adsorption	Fines Migration	Biological Damage	Effect of High Overbalance
Homogeneous Sand-Clean	POSS	POSS	POSS	POSS	POSS	UNL	POSS	POSS
Homogeneous Sand-Dirty	POSS	PROB	POSS	POSS	PROB	PROB	POSS	POSS
Laminated Sand-Clean	POSS	POSS	POSS	POSS	POSS	UNL	POSS	POSS
Laminated Sand Dirty	POSS	PROB	POSS	POSS	PROB	PROB	POSS	POSS
Unconsolidated Sand	POSS	POSS	PROB	UNL	POSS	POSS	POSS	PROB
Fractured Sand Permeable Matrix	POSS	POSS	PROB	POSS	POSS	POSS	POSS	PROB
Fractured Sand Low Permeability Matrix	POSS	UNL	PROB	POSS	POSS	UNL	POSS	PROB
Homogeneous Carbonate	PROB	UNL	POSS	PROB	POSS	UNL	POSS	POSS
Fractured Carbonate Impermeable Matrix	PROB	UNL	PROB	POSS	UNL	UNL	POSS	PROB
Fractured Carbonate Permeable Matrix	PROB	UNL	PROB	POSS	POSS	UNL	POSS	PROB
Vugular Carbonate	PROB	UNL	PROB	UNL	UNL	UNL	POSS	PROB

PROB Probable damage mechanism under most conditions
POSS Possible damage mechanism under specific conditions
UNL Unlikely damage mechanism under majority of conditions

Table 4-1: Potential formation damage mechanism in different reservoir types [23]

CHAPTER 5

5. EFFECT OF FRICTION AND FORMATION DAMAGE ON FLOW BEHAVIOR

In the last few years, many horizontal wells have been drilled around the world. Simultaneously there have been several attempts in the petroleum literature to predict the performance of these wells. In this respect both reservoir aspects and well completion methods have been harnessed to obtain maximum productivity form horizontal well completions.

Joshi [9] mentioned in his book that, while analyzing horizontal well performance, geometric configuration of the reservoir-bedding plane, is of prime consideration. The other important consideration is well completion scheme. One can either have an open hole, insert a slotted liner, insert a liner with external casing packers, or case the hole and perforate the casing, depending upon local completion needs and experience. The type of completion affects horizontal well performance, and certain types of completions are possible only with certain types of drilling techniques. Thus, well length, the well's physical location in the reservoir, the tolerance in drilling location, and the type of completion that can be achieved strongly depend upon the drilling method.

Apart from the above factors that contribute to the horizontal well performance, three other important and rather unpredictable factors are worth to mention. These include formation damage, excessive wellbore friction and encountering unexpected geology [1].

Several authors [3-32] have attempted to evaluate the effect of formation damage both analytically and qualitatively through laboratory procedures. Similarly, some other group of authors [42-54] had tried to evaluate the role of friction on the horizontal well performance. However there has been no direct attempt to evaluate the simultaneous role of distributive formation damage and well bore friction on the horizontal well performance. It has been recognized that horizontal wells can have very complex flow geometry, in part due to interaction between the main flow stream and the influxes along the wellbore, and also due to completion types.

5.1 Impact of Skin Effect on Horizontal Well Performance

The following example from reference [36] gives an idea about the productivity impairment that can result when a skin factor is taken into account. Considering the PI for a horizontal well:

$$PI = \frac{q}{\Delta p} = \frac{k_h h}{141.2 B\mu\left[GF + \frac{\beta h}{L} S\right]} \tag{5.1}$$

In general skin factor S, can be as high as 50 with common values about 20 [36, page36]. Even if it is multiplied by $\beta h/L$, which ranges between, 10^{-2} and 0.3, its effect on the production rate can be substantial. It was shown that for a given set of parameters that yield a GF (geometric factor in equ.5-1) of 2.25, an skin factor of S=20 will result in a 58% reduction of production rate, compared to the case of an undamaged well.

The skin factor 'S', employed and evaluated here, by the method given in reference [10], recognizes the expected conical shape of damage and reservoir anisotropy. However it has been added as a single value into the well performance model. This simplification assumes a constant reduction in the specific productivity index along the well length and is contrary to the original concept of more damage at the heel and lesser at the toe.

In real case, a skin profile is more representative of the actual nature of damage along the horizontal well length. This profile can vary from a steeply declining from well heel to the toe, to a nearly constant one, resulting from approximately a cylindrical damage [20]. A combination of both profiles, that is a constant and a declining one may also be possible [18]. This variable nature of skin is very difficult to accommodate in the conventional productivity models. Hence instead of analytical treatments, through which skin is mostly entered into the productivity models, a numerical solution seems more appropriate to represent the variable nature of skin distribution in the productivity models. Obviously because of this variable skin profile, depending upon the severity of more damage at certain well locations, the inflow performance will vary accordingly. It has already been established that the performance of horizontal well is greatly effected by the distribution of the influx along the well, if the frictional forces are dominant. A variable skin profile is an important contributor to the nature of influx profile along the horizontal well length. In a very recent study [55], it has been proved that if instead of the actual skin profile along the horizontal length, a constant value of the skin is used, than the error in calculating the well performance may be significant. These effects are especially pronounced when friction factor is significant and an error of approximately 100% is reported for selected cases; though the same average value of skin was used but with different variation of profiles.

5.2 Effect of Pressure Drop in Horizontal Well Flow Behavior

Because of frictional losses in flow, there is a pressure drop along the horizontal wellbore. Should this pressure drop be significant relative to drawdown, the pressure far from down hole could nearly equal the pressure in the reservoir, rendering part of the well unproductive. Friction can thus reduce productivity. Systems likely to suffer from this effect include those with long horizontal sections and those with wells of smaller diameter. Most of the analytical work done in the past on horizontal well productivity either assumed that the well is infinitely conductive or the flow is uniform along the entire well length.

5.3 Influence of Fluid Entry Profile on Pressure Drop

Pressure drop through a horizontal wellbore depends upon the fluid entry profile. In the estimation of single-phase calculations an upper most limit of expected pressure drop is obtained if all the fluid is assumed to be entered at the non-pumping end of the horizontal wellbore. The other entry profile is the uniform-flux profile, which assumes the same amount of fluid entry per unit length of horizontal well. As shown in Figure 5-1, depending upon the well-boundary condition either infinite-conductivity or uniform-flux. one would have different flow profiles for the fluid entry into the wellbore. *Additionally, several other fluid entry profiles are possible, depending upon the reservoir heterogeneity, damage profile along the well length and frictional pressure drop.* For example two types of triangular profiles are shown in Figure 5-1. In general larger pressure drop is experienced, when maximum, flux entered is near the toe section of the well. In the different profiles, shown in Figure 5-1. this will corresponds to case C.

5.4 Combined Effect of Formation Damage and Friction on Flow Behavior

A general representation of pressure drop along a horizontal well is shown in Figure 5-2. If the pressure loss is small compared with the pressure drawdown from the reservoir to the well, then the production will increase steadily with well length. This has been shown in Figure 5-3. In this case, therefore. the well length is the limiting well parameter for production.

However if the pressure loss in the well is substantial from the reservoir to the well. then the farther parts of the well will have a very small influx, so production will increase only marginally with length. In this case, therefore well diameter is the limiting well parameter for production.

The damage skin profile in a horizontal well may look like as shown in Figure 5-4, with skin damage at the heel being higher than at the well toe. This kind of damage profile in general affects the fluid influx in such a way that more fluid will enter near the toe section of the well. The resultant flux is a decreasing profile along the well length, as shown in Figure 5-5.

It is evident from the discussion and by looking at the Figures 5-2 to 5-5, that both friction and damage profile affect the influx in horizontal wells in opposing fashion. This may lead to conclusion that in some cases, the combined effect will be a uniform influx along the well length. However the fact cannot be ignored that because of the damage profile larger intake of fluid is at the toe side of the well. This may add additional friction pressure drop, because of the nature of influx profile. An exact prediction of the combined effect is somewhat indecisive unless a proper knowledge of the overriding factor is already explored. It depends to a greater extent, on the type of completion, reservoir aspects and nature and distribution of damage along the horizontal well.

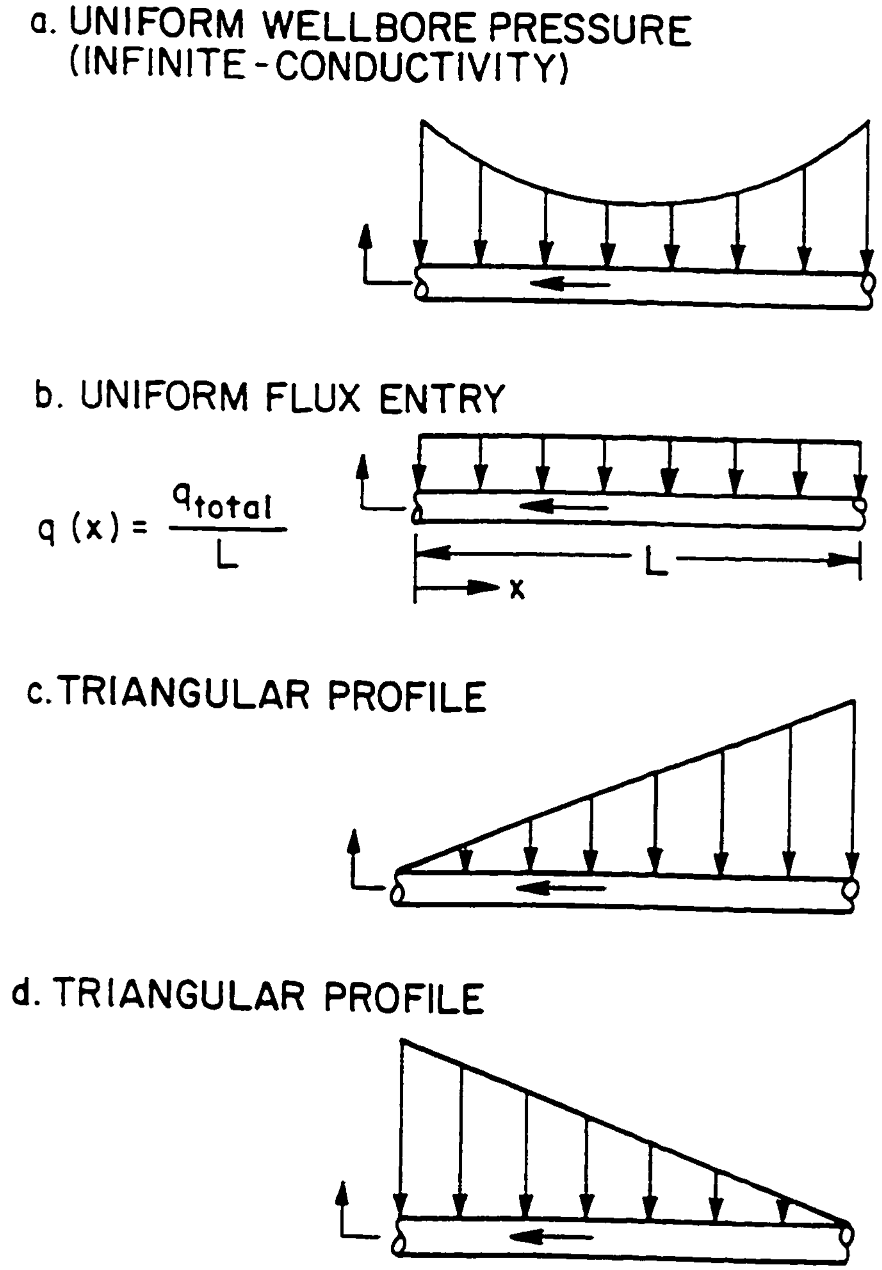

Figure 5.1: Some of the entry profiles into a horizontal well. [9]

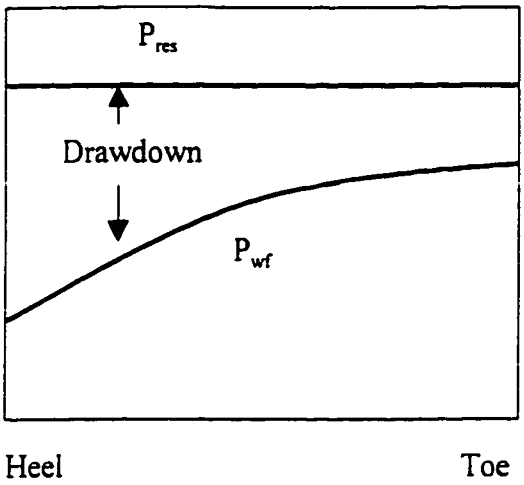

Figure 5.2: Decreasing well flowing pressure, along horizontal well length.

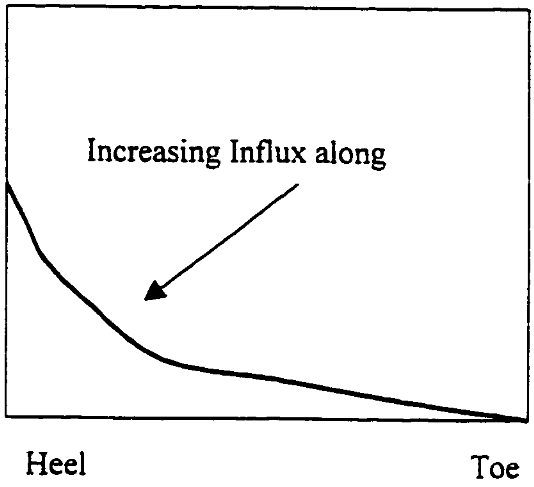

Figure 5.3: Increasing influx along horizontal well length.

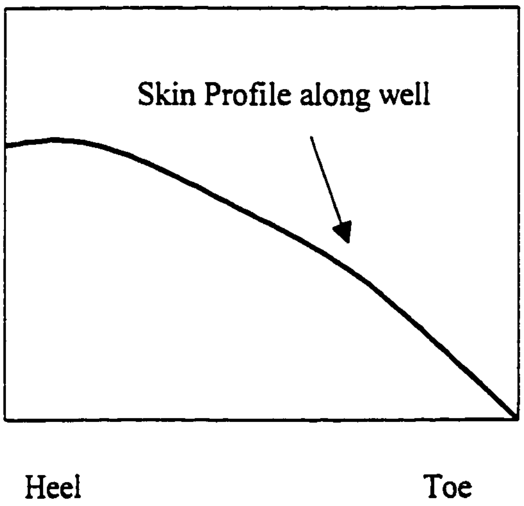

Figure 5.4: General skin Profile along the horizontal well length.

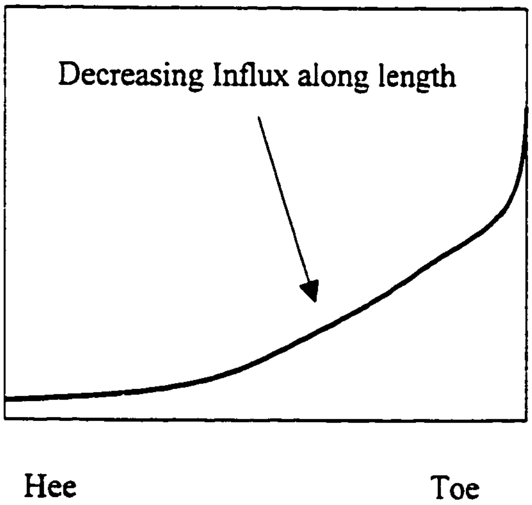

Figure 5.5: Decreasing influx along the horizontal well length.

CHAPETR 6

6. METHOD OF ESTIMATION FOR HORIZONTAL WELL PERFORMANCE

Computer modeling is being used as a tool to solve many of the mathematical equations that are difficult to solve on paper, especially the ones having successive summation series and integrals and require iterative procedure for solution. Using computer modeling as a tool, not only these equations are solved but various equations and mathematical models can be coupled together. In this way the synergy of various elements and the overall performance of a given problem can be examined.

In this study computer modeling in FORTRAN language is employed to evaluate the overall performance of the fluid flow related with horizontal wells that are either partially and selectively perforated or are open holes. The modeling approach used here, conglomerate various individual performances that contribute to the overall well productivity. These include,

- Reservoir inflow performance in terms of specific productive index,

- Length and distribution of perforated or open sections, in case where well is cemented and perforated.

- Nature and distribution of various skin effects along the horizontal well length. These include mostly the damage imparted near the well bore by drilling fluids and productivity of perforations etc., and

- Out flow performance corresponds to two-phase Well bore hydraulics that takes into account various types of flow regimes and loss in fluid head in terms of acceleration. kinetic and frictional pressure gradients.

Figure 6-1, represents the schematic of the approach that has been adopted here. As can be seen, various individual performances are taken into consideration to predict the combined performance.

6.1 INFLOW PERFORMANCE

In the early age of technology, horizontal wells were completed as open holes or with slotted liners. Accordingly, the models that have been developed to investigate the response of horizontal wells assume that the entire drilled length of horizontal well is productive.

Production problems encountered over the years and the need for workover operations dictated the necessity to develop new completion techniques. Cemented completion and completion with external casing packers are now among standard completion choices for horizontal wells. An important feature of these new completion techniques is selective completion of the well; that is, unlike the open hole or slotted liner completion, only segments of the well are open to flow. These completions are shown in Figure 6-2.

As horizontal well technology has developed, several inflow formulas for horizontal wells have been presented [9]. Goode and Wilkinson [33] first time presented the inflow performance of partially open horizontal wells. They used no-flux condition on all the external boundaries, with inflow performance related to long-time behavior of constant-rate pressure. A general representation of such inflow performance is given by;

$$J = \frac{7.08 \times 10^{-3} k_{He} h}{\mu B_o (p_{ID} + skin)} \tag{6-1}$$

The dimensionless inflow pressure is expressed as a sum of two pressure drops i.e.,

$$p_{ID} = S_{zD} + p_{xyD} \tag{6-2}$$

The part 'p_{xyD}' is called 2-D fracture contribution. This is the dimensionless pressure in the x-y plane resulting from the treating the well as a set of fractures that fully penetrate the formation.

The part 'S_{zD}' is an additional skin that results because the well does not fully penetrate the formation and flow must converge near the well. See appendix [A] for detailed formulation.

The analytical formula presented here can be used to determine the inflow pressure for horizontal well that has several open intervals placed arbitrarily along the drilled length of the well. The results show that, in many cases, the open length of the well can be reduced considerably without a substantial decrease in the well performance. This is particularly true if the drainage region is thin and areally large.

The analytical formulations presented by Goode and Wilkinson are programmed in FORTRAN language, after transformation of some of the variables as shown in the appendix [A]. The productivity index value obtained is divided by the total length of the open segments to obtain the specific productive index. Similarly the openhole well specific productivity index can also be obtained.

6.2 SKIN DISTRIBUTION ALONG THE HORIZONTAL WELL

With the spread and advancements in horizontal well technology around the world. the issue of formation damage and skin distribution along the horizontal well come in prominence again and have been viewed differently from the conventional skin in vertical wells. Many factors can contribute to the productivity impairment in a horizontal well. However in general drilling induced formation damage and effectiveness of the perforated completion are the over riding factors. Various models [10,18,19,20] for skin distribution along the horizontal well are used to see the behavior they impart on production performance.

Karakas and Tariq [45] have presented semi-analytical productivity models for perforated completion. They also showed, that damage and perforations can be characterized by a composite skin. This composite skin distinguishes between perforations terminating either inside or outside the damaged region. The study differs the conventional idea of simply adding the skins arrived from drilling damage and perforated completion.

The semi analytical solution for the perforation skin effect is divided into three components: the plane flow effect, S_H; the vertical convergence effect, S_v; and the well bore effect, S_{wb}. The total perforation skin effect is then,

$$S_p = S_H + S_V + S_{wb} \tag{6-3}$$

Figure 6-3, gives all the relevant variables for the calculation of the perforation skin components. The method for the estimation of each individual component is used as described in the reference [45].

Karakas and Tariq also showed that for perforations terminating inside the damage zone the 'damage skin' analogous to Hawkin's formulation is given by,

$$S_{dp} = \left(\frac{k}{k_D} - 1\right)\left[\ln\left(\frac{r_d}{r_w}\right) + S_p\right] \tag{6-4}$$

Whereas the total skin factor is given by,

$$ST = S_{do} + \left(\frac{k}{k_D}\right)(S_p \tag{6-5}$$

The flow behavior into perforations drastically changes for perforations extending beyond the damaged zone. For highly damaged formation, the effective perforation length is reduced to the penetration out side the damaged zone. Also the effective well bore radius increased to the damaged zone radius. For formations having finite permeability in the damaged region the well radius and perforation length is modified by.

$$lp' = lp - \left(1 - \frac{k_D}{k}\right) ld \qquad (6\text{-}6)$$

$$r_w' = r_w + \left(1 - \frac{k_D}{k}\right) ld \qquad (6\text{-}7)$$

The total skin in this case corresponds to the perforation skin. S_p, that would be obtained from the modified length and radius. These equations are programmed and used in the main program.

6.3 OUT FLOW PERFORMANCE

The flow behavior in horizontal section, which has an increasing flow rate along it caused by influx from the reservoir, and the relationship between the pressure drop and the influx has been recognized as an important problem in production engineering. The flow behavior and the relationship between the pressure drop and the influx are the essential items of the information in the proper design of a horizontal well.

The assumption of a constant pressure along a horizontal wellbore, which is used often for well-test analysis and reservoir simulation for horizontal wells, must be examined carefully. Neither a uniform-flux nor a uniform-pressure boundary condition in a well bore is realistic. Some pressure drop from the upstream end of a horizontal wellbore to the downstream end is essential to maintain fluid flow within the wellbore. This condition is particularly true when two-phase flow, including a compressible gas phase, is encountered in the wellbore. For the production of the single phase liquid, pressure drop along the well bore may be neglected, except for a high-viscosity liquid, high reservoir permeability of a few darcies, or high production rates in excess of few thousand reservoir barrels/day. The flow behavior in the horizontal well differs from that in a regular pipe. The wall roughness of a horizontal well can be much higher than that of a regular pipe because of the perforations or slots. The influx along the well bore can change the pressure drop in the well bore. This pressure distribution not only effects the production behavior, but also is influenced by the well completion and well configuration.

The effect of frictional losses is more pronounced in horizontal well bores, that are cased, cemented and selectively perforated where the fluid may enter the wellbore at various locations along the horizontal well length. The distance between perforation may not be sufficient to achieve a stabilized velocity profile. In other words, the length and distribution of the perforated intervals along the horizontal wellbore affects the wellbore hydraulics. However, in long horizontal wells with large diameters, the disturbance of flow by fluid influx from the perforations may not be significant. This makes the use of conventional pipe flow pressure correlations for calculating the frictional losses along the horizontal wellbore legitimate.

To predict the pressure drop along the horizontal well, modified two-phase Beggs and Brill [35,36] correlation is employed which can be applied to any well bore inclination and flow direction. The method employed general mechanical energy balance and the in-situ average density to calculate the pressure gradient in terms of acceleration, potential and frictional pressure gradients given by the differential equation.

$$\frac{dp}{dz} = \left(\frac{dp}{dz}\right)_{PE} + \left(\frac{dp}{dz}\right)_{KE} + \left(\frac{dp}{dz}\right)_{F} \tag{6-8}$$

Different horizontal flow regimes like, segregated, transition, intermittent and distributed; based on the correlating parameters are also considered.

6.4 OVERALL PERFORMANCE

Overall performance of horizontal well is not only governs by the type of completion, but also by the frictional effect and distribution of skin along the length. In general frictional effect magnitude and its influence on the inflow performance can be comprehended but presence of variable nature skin distribution along the length add difficulty in the prediction of the well performance.

Ref. [44] employ a detail list of various attempts in the area where well bore is coupled with the reservoirs. It is shown that the previous work can be categorized into three types:

- Models for well that are infinitely conductive and thus are not influenced by the amount of pressure drop in the well'

- Models where the reservoir is represented by an analytical model for single phase flow, and

- General models that couple multiphase flow-simulators with well.

In most of the earlier work done in the area, general distribution of skin along the well length has been ignored or addressed abundantly. There has been no general assessment in the literature about the combined behavior of skin and friction on horizontal well flow performance.

In this study, we have employed computer modeling as a tool to combine the influence of both friction and skin distribution to predict the overall performance of horizontal well. Refer to Figure 6-4, the well consists of finite no. of open segments that amount for certain open percentage of the well. The specific productivity index obtained form the inflow performance is no longer constant along the well length because of the skin distribution. The flow rate into the wellbore is compounded along the length from the toe to heel as each open segment contributes to the production.

The influx to each open segment is assumed by dividing the segment into 'n', finite-sections. This approach relates with finite difference scheme. Flow rate into the section is obtained by;

$$q^{nth} = J_h^{nth} \times (P_R - P_{TOE}) \times (Lp / n) \tag{6.9}$$

Based on the flow rate obtained the pressure drop in the n^{th} section of the well bore is estimated form the correlations [35,36]. As the fluid enters the next section it experiences another addition of influx from the reservoir. A certain differential pressure is assumed and influx is calculated i.e., 'P_{Toe}' in the equ. (6.9) is replaced by 'P_{wf}'. The methodology is repeated in an iterative way until accurate prediction of both pressure and flow rate distribution is obtained. This has been shown in the flow chart as shown in the Figure 6-5.

To acquire more realistic performance several utility programs are also employed to account for changes in the fluid properties with the variation in the pressure along the well length while the temperature is assumed constant. These include calculation of Z-factor, formation volume factors, gas and oil viscosity, and solution GOR etc. The main program flow chart and methodology used is shown in Figure 6-6. A sample input data file and the output obtained from the program is shown in the Appendix [B].

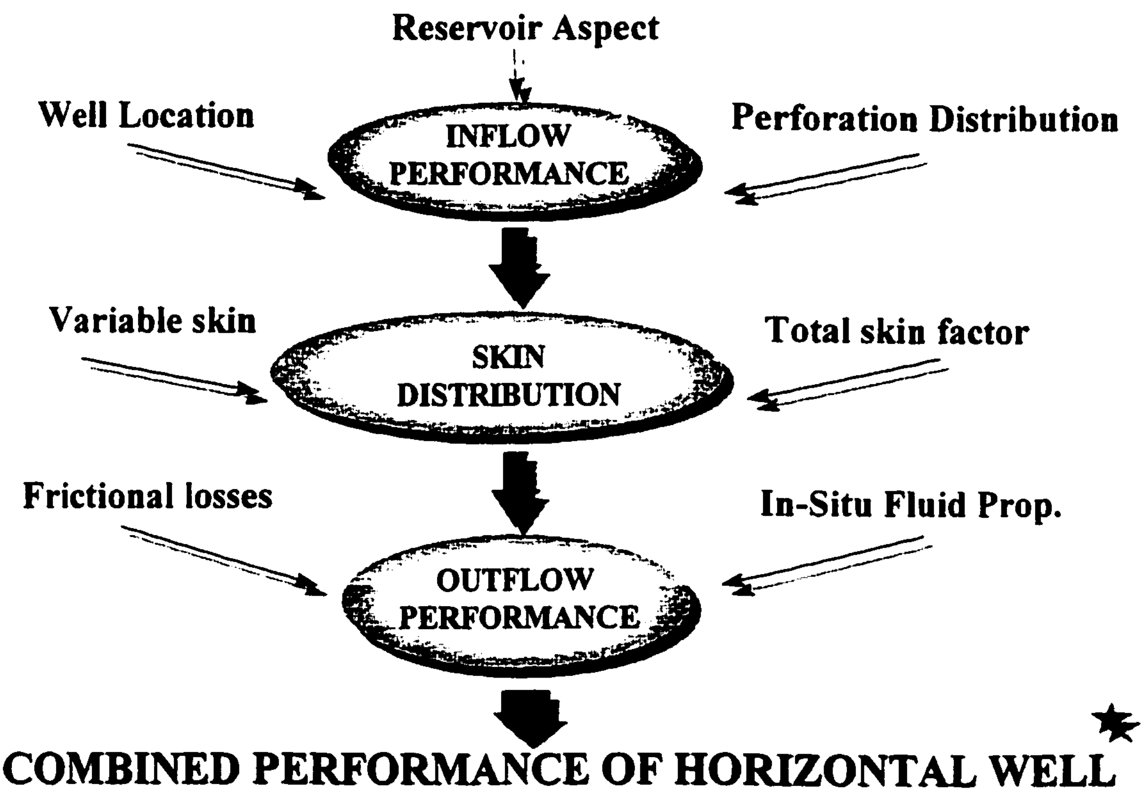

Figure 6-1: Schematic, showing the synergy of various elements in combined performance of horizontal wells.

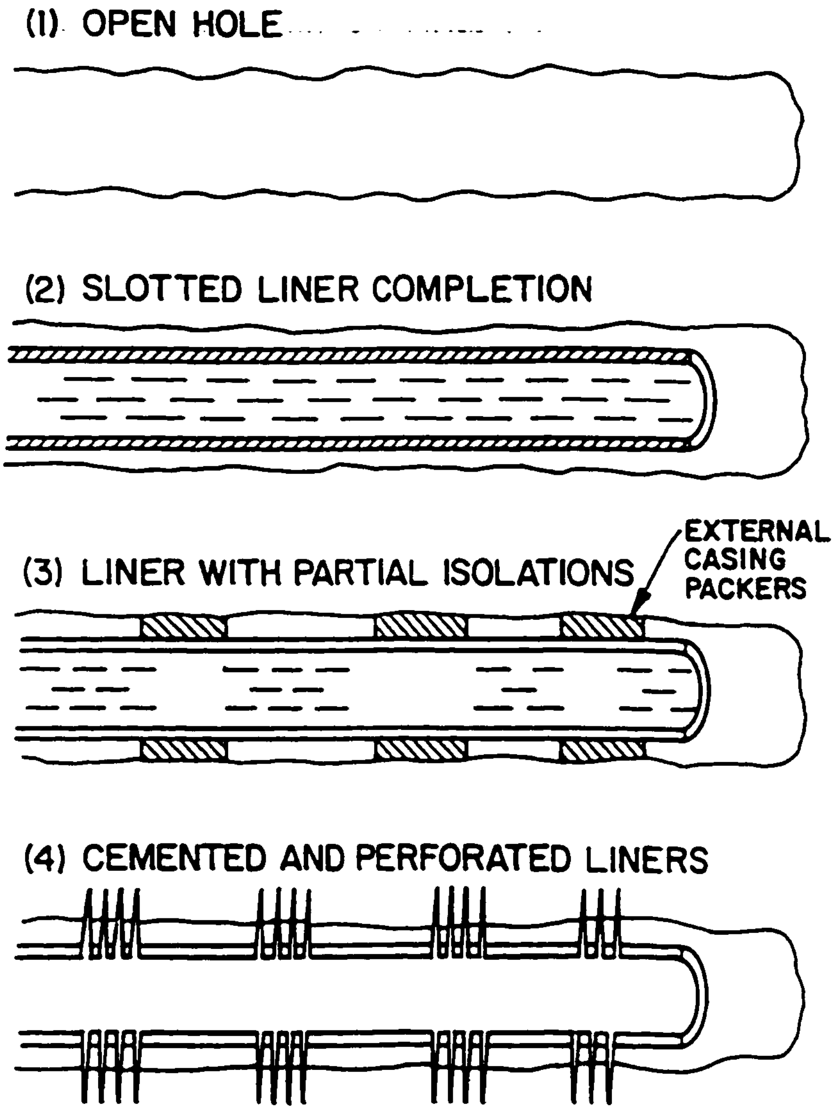

Figure 6.2: A schematic of various completion techniques for horizontal wells [9]

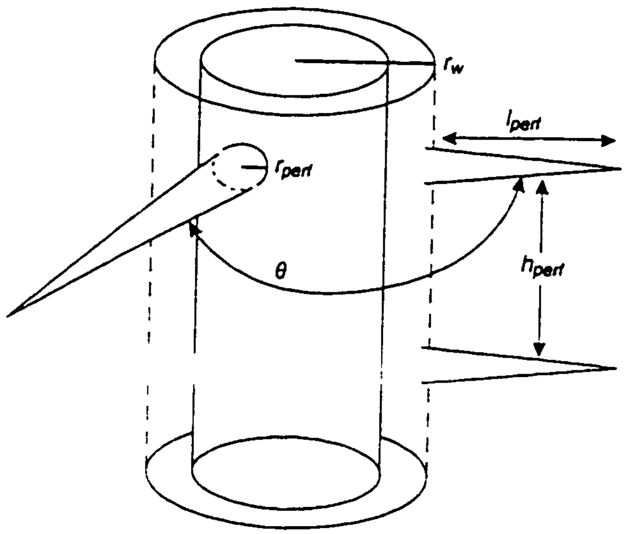

Figure 6-3: Well variables for perforation skin calculation. [36]

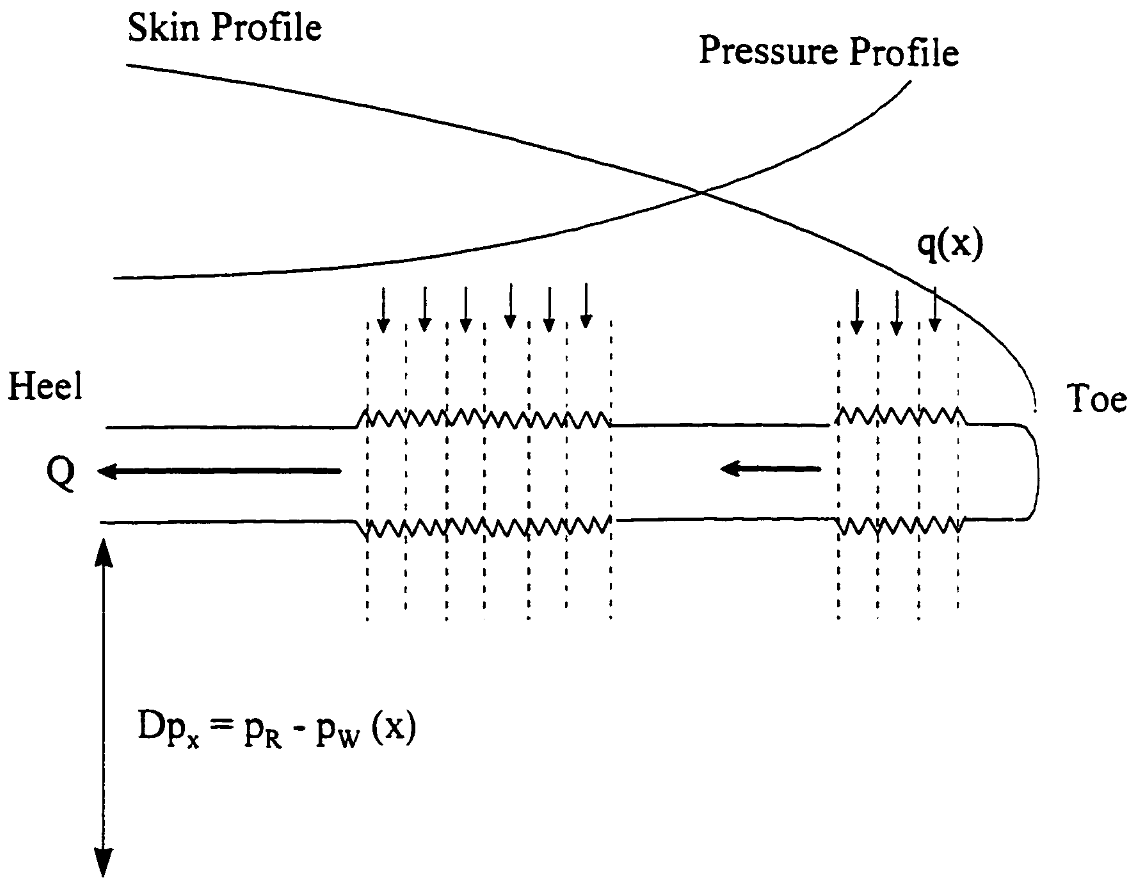

Figure 6-4: Schematic of horizontal well flow performance.

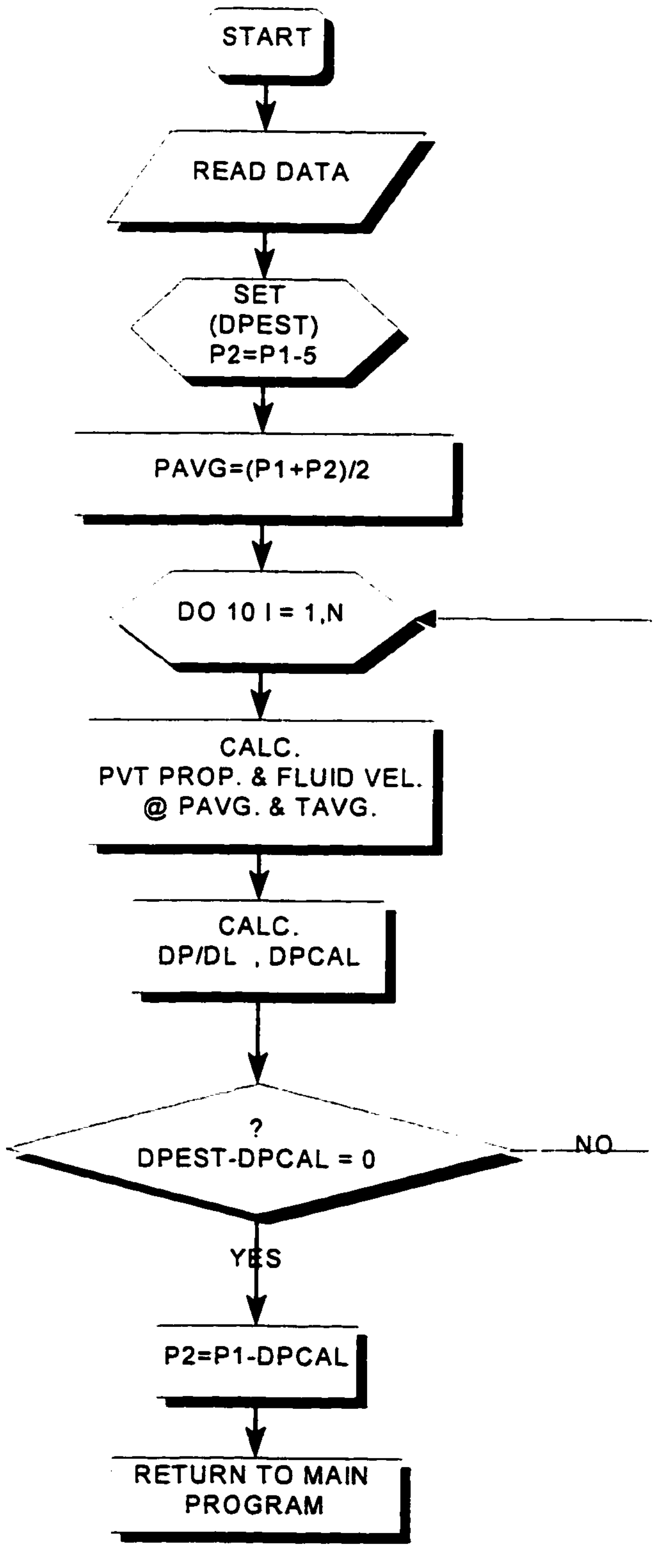

Figure 6-5: Flow diagram showing the methodology for iterative pressure drop calculations.

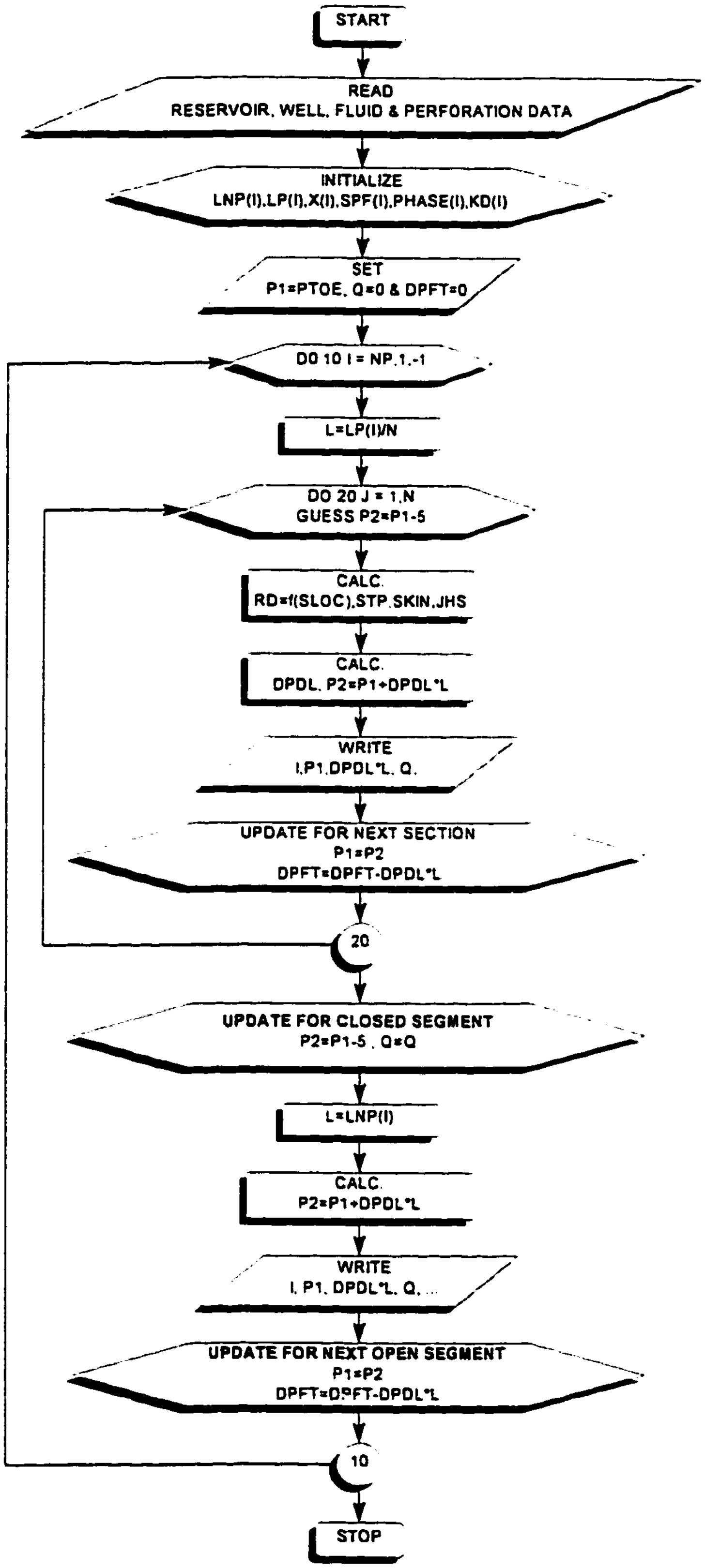

Figure 6-6: Main program flow chart.

CHAPTER 7

7. Validation and Field Application

7.1 CASE STUDY

A real field example of a horizontal well drilled and completed as cased hole is used to match the simulated results with the measured flow meter data from the well. Table 7-1, shows the related data used and Table 7-2 shows the contribution and distribution of different open segments of the well.

It is evident from Figure 7.1 that a good match between the measured flow meter data and the simulated data has been obtained.

7.2 DISCUSSION

The field analysis indicated that the actual well Productivity Index measured was 186 bbl/day/psi. There was no information available about the distribution of damage along the well that may have occurred during the drilling process or on the effectiveness of the perforation job.

Further the analysis of the flow meter run in this well on September, 1994 indicated that around 100ft (8.7% of well length) of the perforated intervals were not contributing to flow at all, while around 240ft (21% of well length) of the well contribute only 13% of the total production.

In the simulated results the ideal Productivity Index obtained form the Inflow Performance of the well was found to be 282 bbl/day/psi. This can be attributed to the formation damage and the productivity of the perforated sections. A skin profile is evaluated for the well that takes into account both drilling induced damage and skin because of the perforations. This skin profile is shown in fig 7-2. As mentioned above, a good match of the measured flow meter data has been obtained taking into account an assumed skin profile distribution.

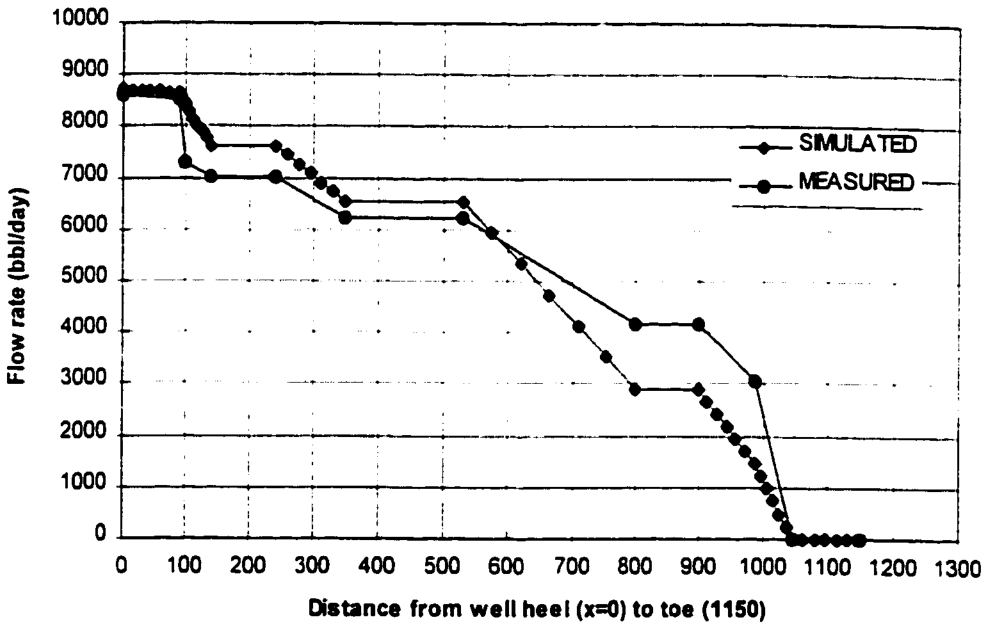

Figure 7-1: Field example case matched with the simulated results.

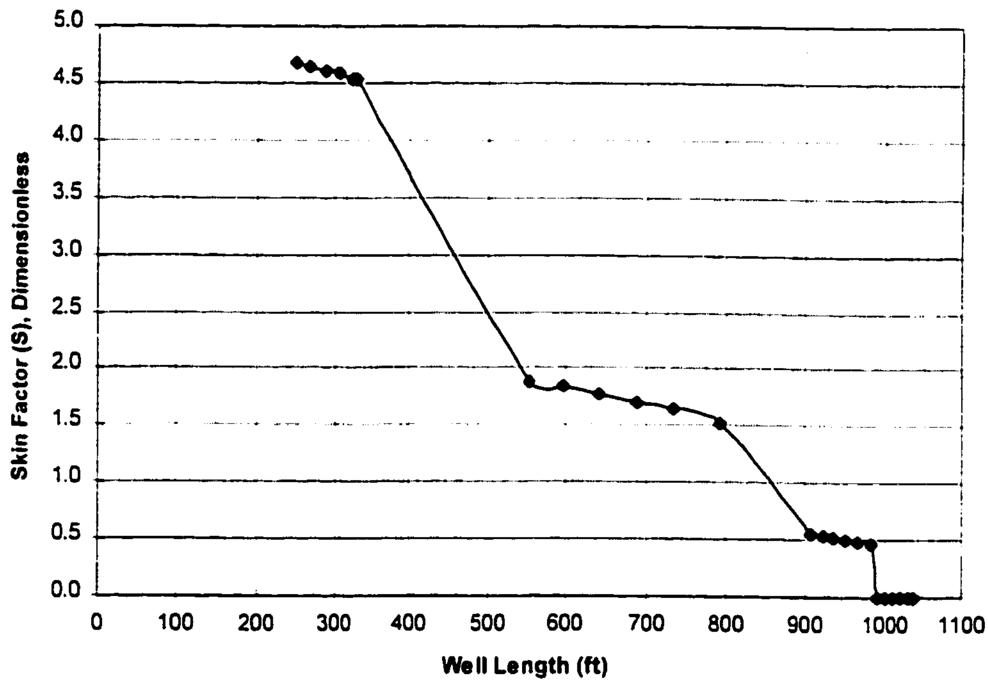

Figure 7-2: Skin profile along the horizontal weli

Table 7-1: Field Example Data

k_{avg}	2700md
H	100 ft
L_w	1150 ft
N_p	8
Open % of the Well	67 %
D	0.523 ft
P_R	2297 psia
T_R	160°F
Q_o	8800 bbls/day
°API	28.0
S_g	0.90
Rs_{oi}	100 res.bbl/scf

Table 7-2: Field Case Flow Meter Analysis Report

No.	Interval feet	Production Rate (bbl/day)	Percent of Total flow	Perforated Feet	Specific Rate (bbl/day/ft)
1	7200-7290	101	1	90	1
2	7290-7300	1229	14	10	123
3	7300-7340	275	3	40	7
4	7440-7550	765	9	110	7
5	7730-8000	2100	24	270	8
6	8100-8187	1084	13	87	12
7	8187-8247	3066	36	60	51
8	8247-8350	0	0	103	0
Total		8620	100	770	

CHAPTER 8

8. PARAMETRIC STUDY

It has been shown earlier that a good match has been obtained between the actual field flow meter data and the simulated data, obtained from the computer model that has been developed. After the successful match, we proceed in this chapter with a planned parametric study. The objective is to evaluate the influence of critical parameters like well open percentage, length, diameter and reservoir height and anisotropy etc., with special emphasis on the degree of formation damage. The concept of representing skin as a single and constant parameter in the general productivity models and effect of selective stimulation has also been investigated.

The data used in this parametric study is taken from the Middle East. Table 8.1, shows this data, as well as the variation range for some of the selected parameters.

Figure 8.1 shows the reservoir and well bore model. As illustrated in this figure, the well is located in the center of a homogeneous, non-isotropic, rectangular reservoir, bounded by no flow boundaries. Further the well consists of uniformly distributed, five open segments of equal lengths along the well bore.

Table 8-1: Parametric data

Parameter	Units	Value
Reservoir Length (L_x)	Ft	4000
Reservoir Breadth (L_y)	Ft	2000
Reservoir Height (h)	Ft	20 to 100
Well Length (L_w)	Ft	1000, 2000& 3000
Diameter (D)	Ft	0.375 & 0.5
Permeability ($k_x = k_y$)	md.	2500
Vertical Permeability (k_z)	md.	1000 to 2500
No. of Open Segments	#	5
Well Open Percentage	%	20 to 100
Reservoir Pressure	Psi	2250
Pressure at the Toe	Psi	2220
Oil Gravity	°API	30
Rsi	Scf/bbl	400
Gas Gravity	Fraction	0.9
Reservoir Temperature	°F	160

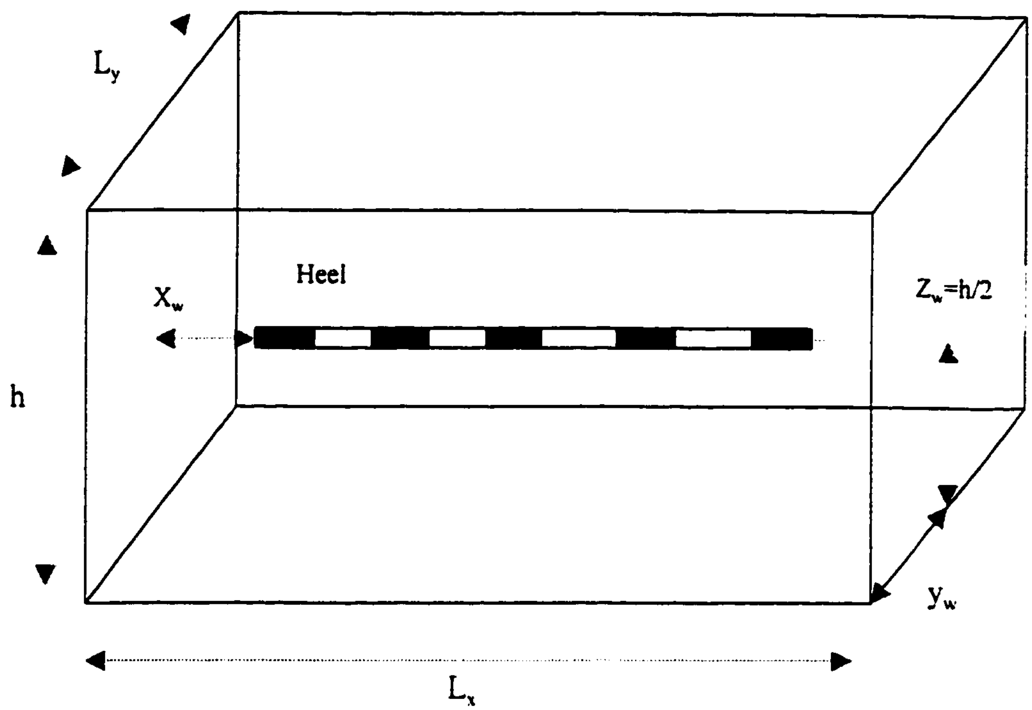

Figure 8-1: Reservoir and wellbore model.

8.1 Defining Dimensionless Parameters

In order to generalize some of the results in this study, we have defined following dimensionless numbers:

Dimensionless Length, LD

$LD = L_w / L_x$

Where, L_w is the well length and L_x is the reservoir length.

Dimensionless Height, HD

$HD = h / L_x$

Where h, is the reservoir height.

8.2 Effect of Different Skin Profiles

In this section we have evaluated the error that can occur when a single value of skin is taken as a representative of productivity impairment in the productivity models. It has been generally accepted that damage along the horizontal well occurs more at the heel and less at the toe. This kind of variable damage along the length can only be characterized by a representative skin profile, not by a constant value.

Based on the assumption, for a well of 1000ft a given invasion depth of 60 inches at the heel and zero at the well toe is considered. The skin factor is evaluated based on the Economides [10] method. This skin factor is found to be 14. Based on this skin factor a constant skin profile is considered along the horizontal well; which is referred as case-1 in Figure 8.2. Similarly three other skin profile are also considered based on the same average value of 14. In the second case, a linear decrease in the profile is considered from the well heel to well toe. This is called case-2. In the third profile called, case-3 the skin profile is calculated based on the Yan's paper [20] and in case-4 a polynomial decrease in the skin profile [9] is considered, keeping the same average value of 14. This has been shown in Figure 8.2.

Based on the above skin profiles well performance is calculated for well length of 1000ft and diameter of 6 inches, while case-1 is taken as base case. This is shown in Figure 8.3. The pressure profiles for the different cases of skins are also plotted in Figure

8.4. The cumulative flow rates given in the figure are reported in the dimensionless form by reference to the base case. To investigate the effect of friction the well performance is also plotted for a diameter of 4.5 inches. The well performances and pressure profiles in this case are shown by, Figure 8.5 and 8.6, respectively. The maximum pressure drop as shown in Figure 8.6, here is only 3 psi from well toe to heel.

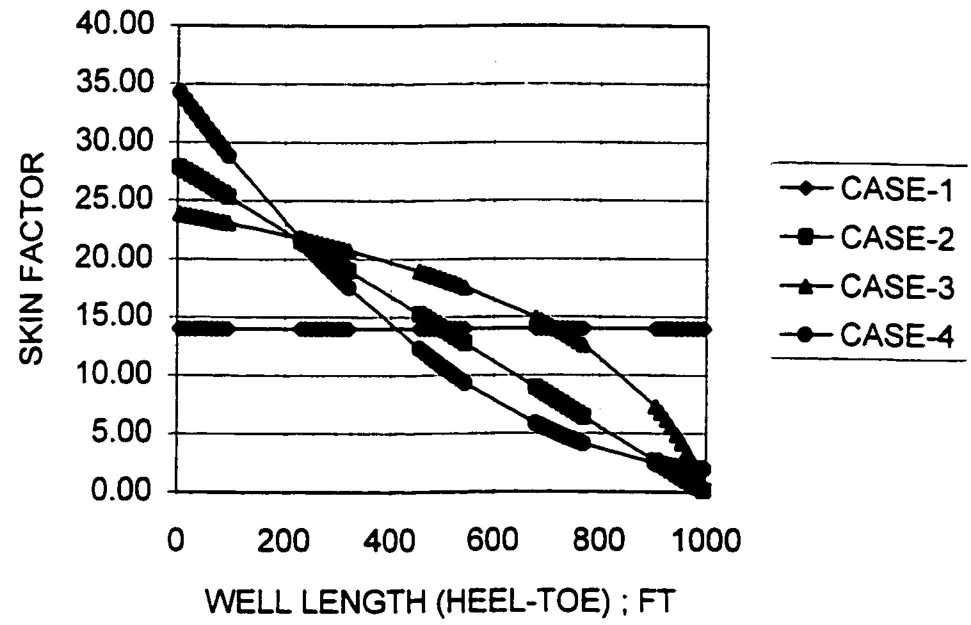

Figure 8.2: Four Cases of Selected Skin Profiles for L=1000ft (Savg=14)

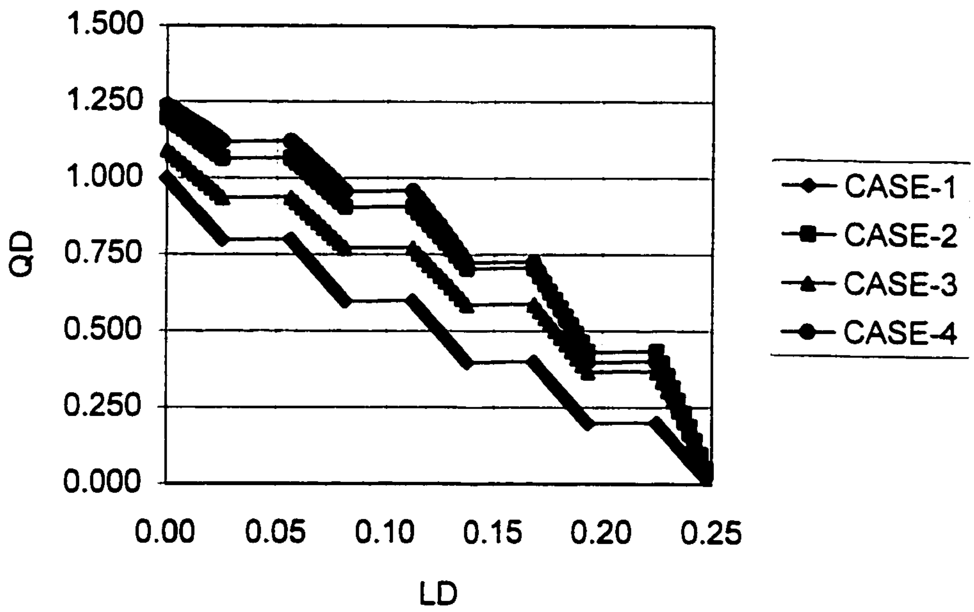

Figure 8.3: Well Performance with Different Cases for LD=0.25 & Dia=0.5ft

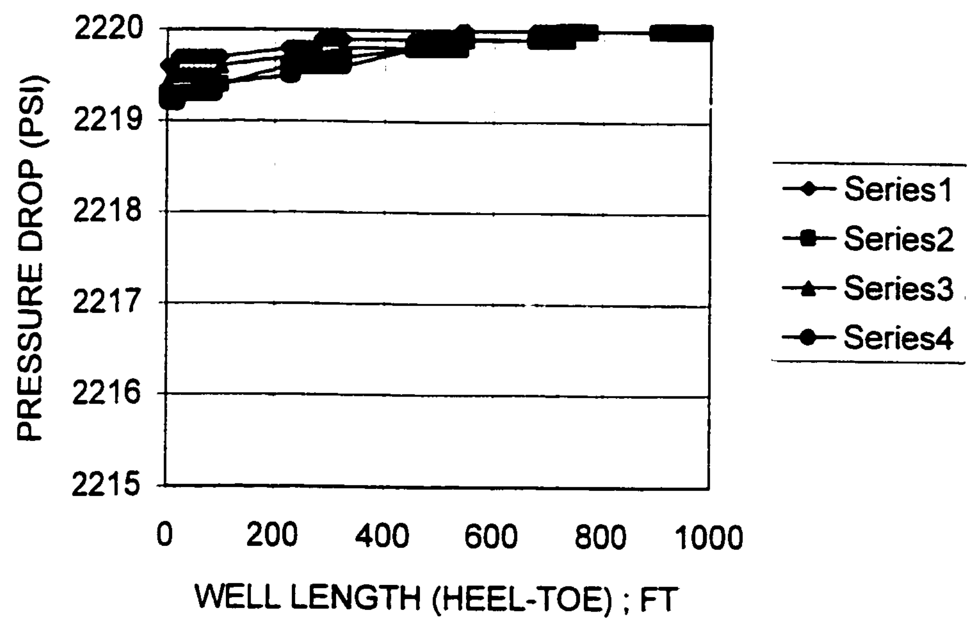

Figure 8.4: Pressure Profiles with Different Cases for LD=0.25 & Dia.=0.5ft

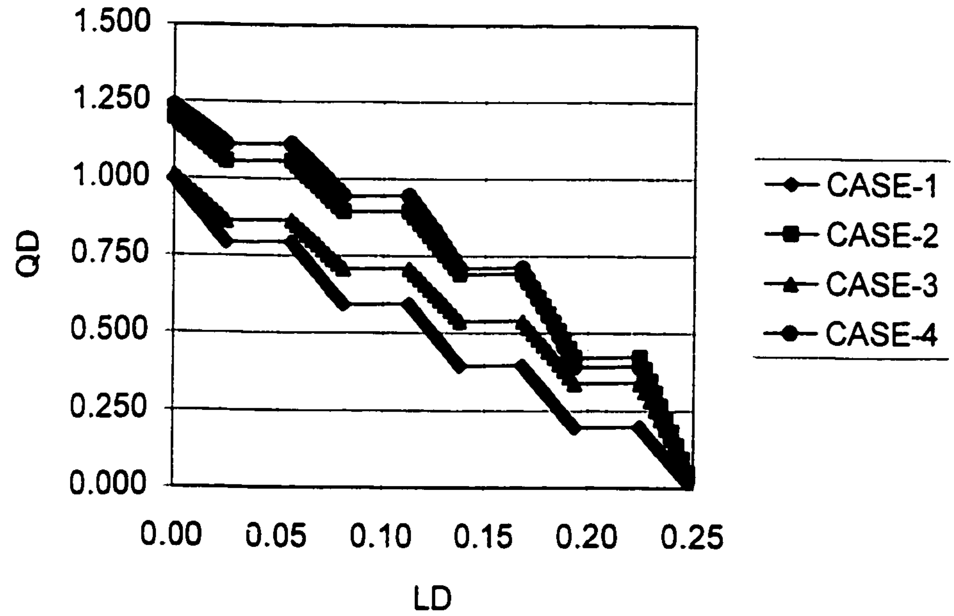

Figure 8.5: Well Performance with Different Cases for LD=0.25 & Dia=0.375ft

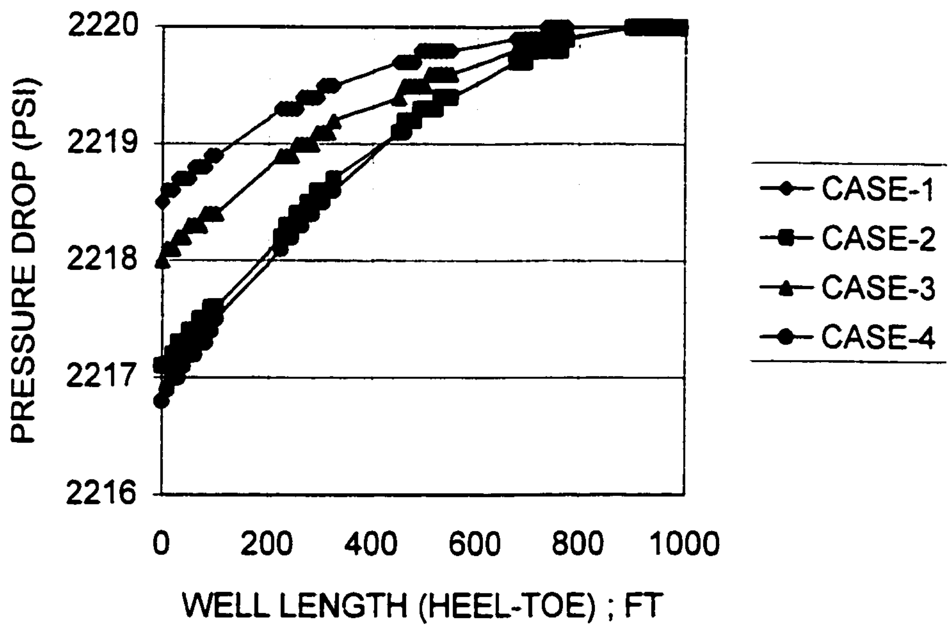

Figure 8.6: Pressure Profiles with Different Cases for LD=0.25 & Dia.=0.375ft

To investigate the effect of length, the experiments are also repeated for well length of 2000ft and 6 inches in diameter. In this case a relatively higher value of average skin equal to 20 is taken as the base case. This has been shown in Figure 8.7. The well performance and corresponding pressure profiles are plotted in Figures 8.8 and 8.9 respectively. The experiment is repeated for diameter of 4.5 inches, and well performances for different skin profiles are plotted in Figure 8.10. Pressure profiles are plotted in Figure 8.11. The maximum pressure drop associated here is 4.5 psi.

Similar sets of experiments are repeated for well length of 3000ft. The average value of skin here is 24. See Figure 8.12. The well performance and corresponding pressure profiles are plotted here from Figures 8.13 to 8.16. The maximum pressure drop associated with case-4 profile is 18 psi and 100 psi for well diameters of 6 and 4.5 inches respectively.

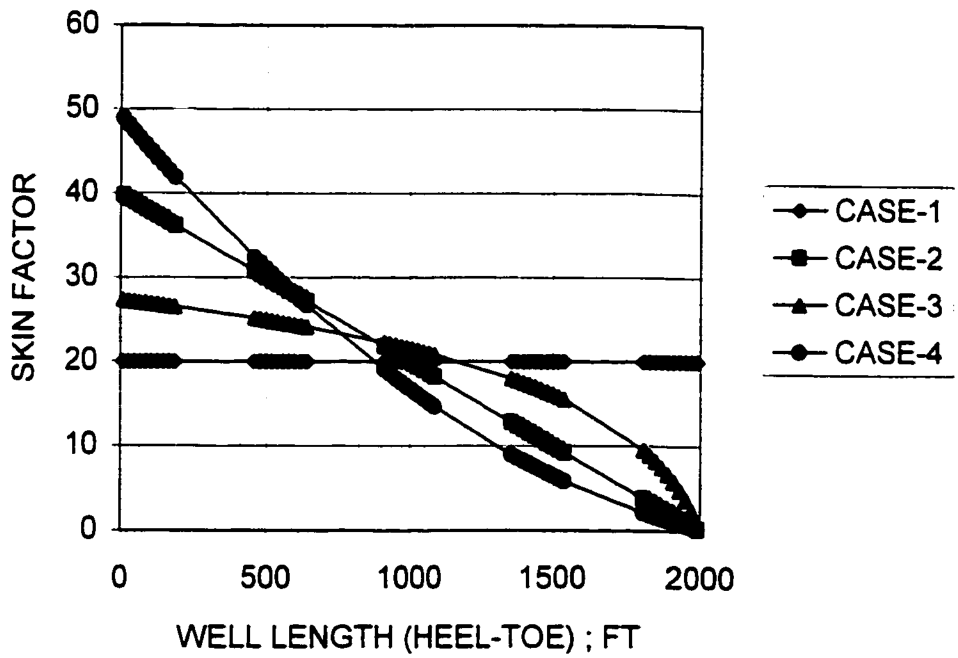

Figure 8.7: Four Cases of Selected Skin Profiles for L=2000ft (Savg=20)

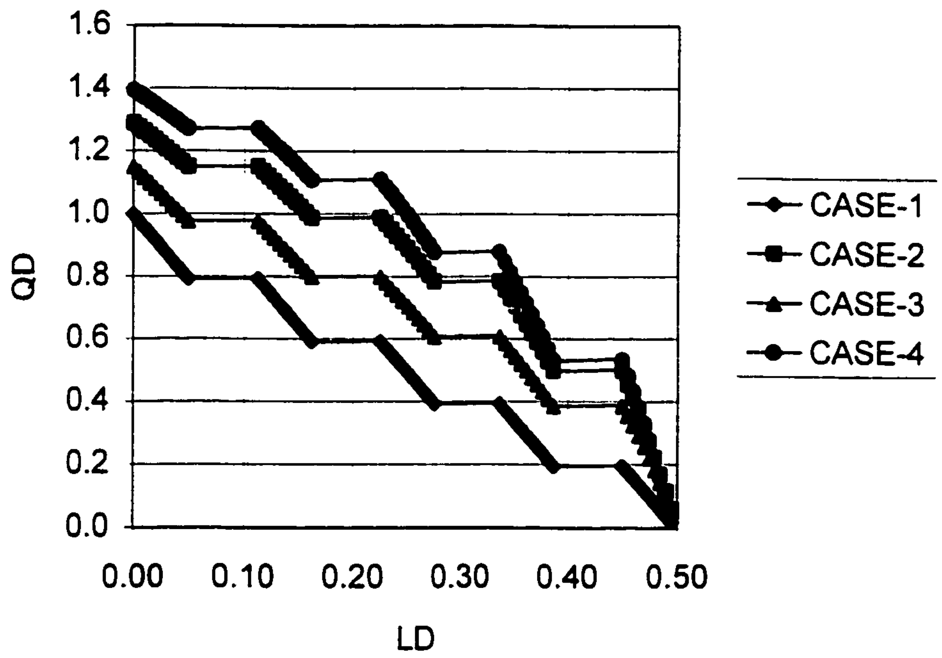

Figure 8.8: Well Performance with Different Cases for LD=0.50 & Dia=0.5ft

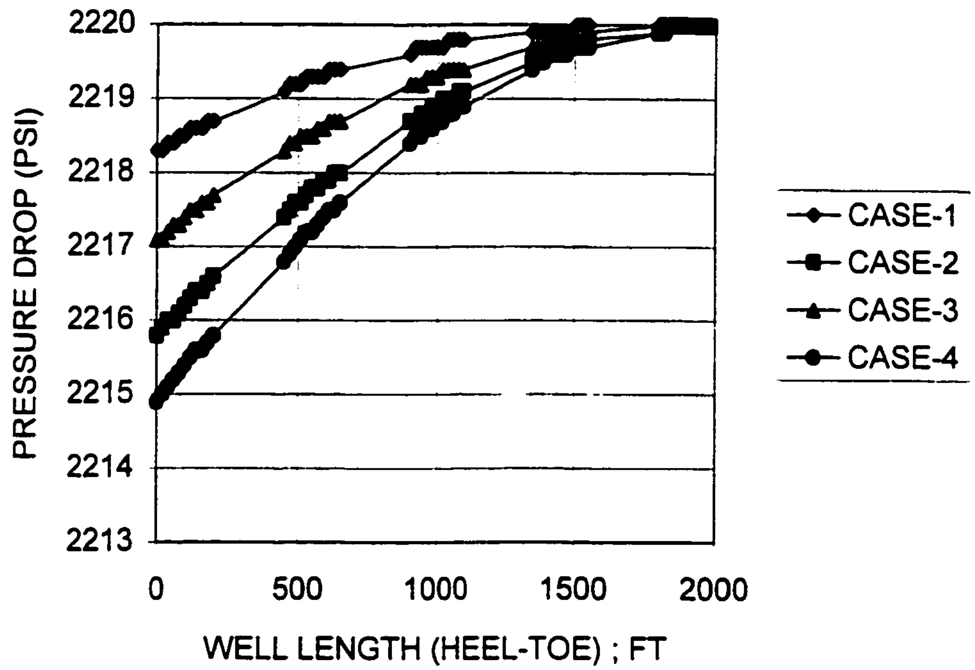

Figure 8.9: Pressure Profiles with Different Cases for LD=0.50 & Dia.=0.5ft

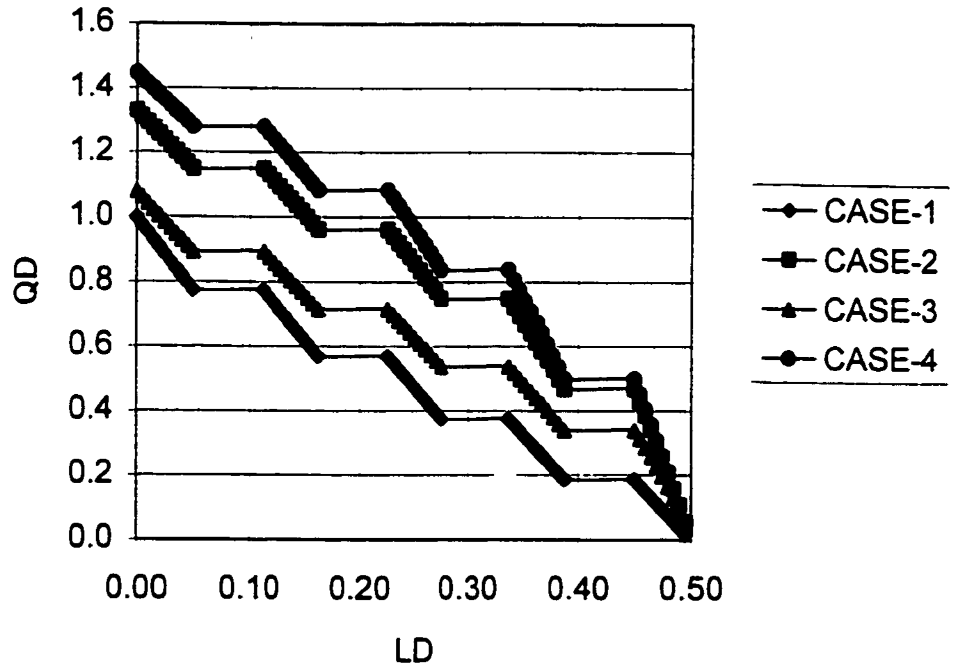

Figure 8.10: Well Performance with Different Cases for LD=0.50 & Dia=0.375ft

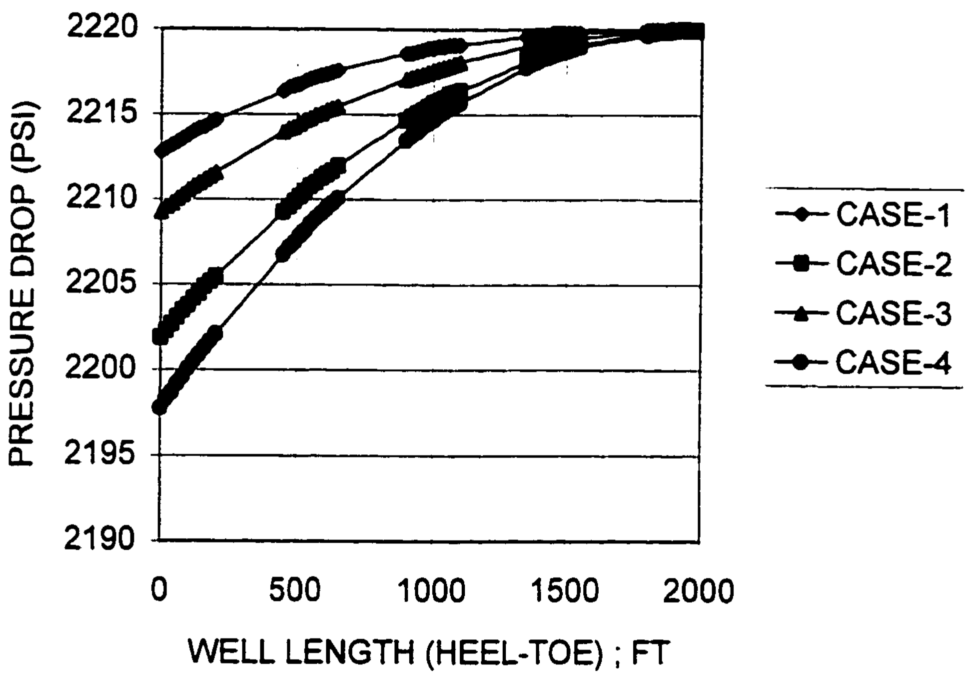

Figure 8.11: Pressure Profiles with Different Cases for LD=0.50 & Dia.=0.375ft

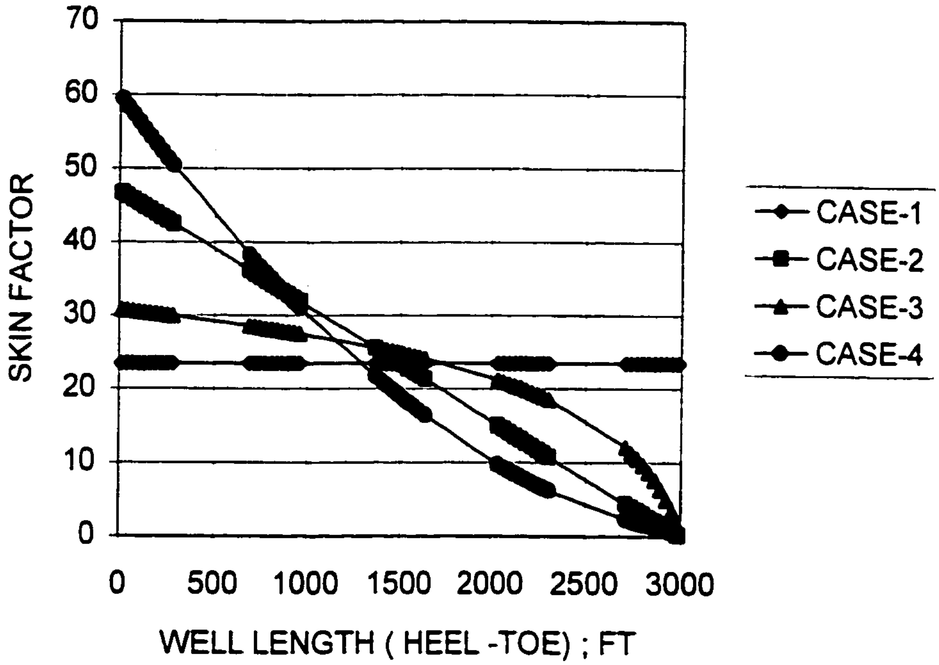

Figure 8.12: Four Cases of Selected Skin Profiles for L=3000ft (Savg=24)

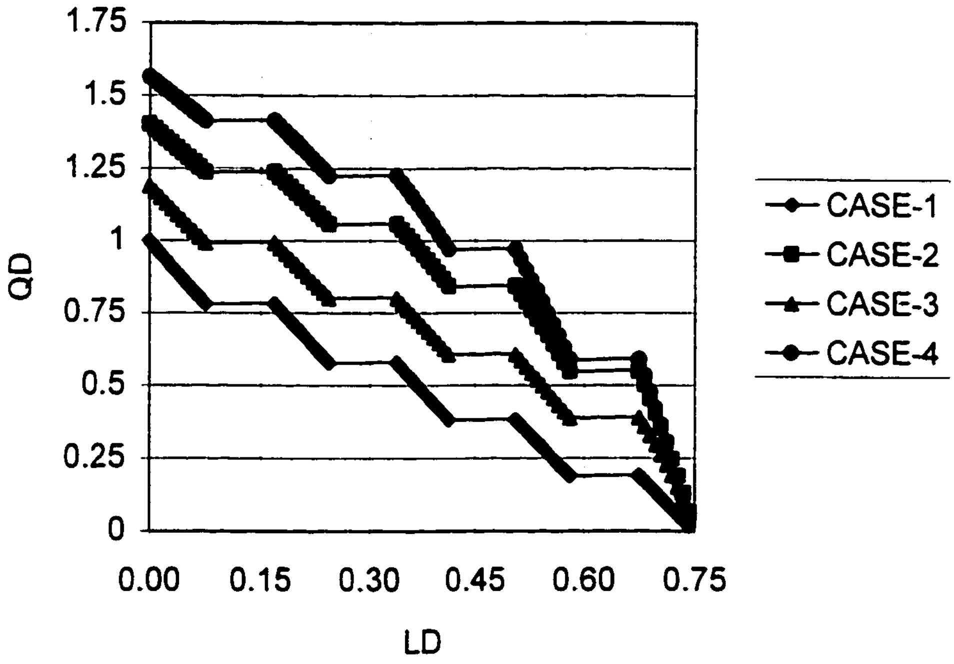

Figure 8.13: Well Performance with Different Cases for LD=0.75 & Dia=0.5ft

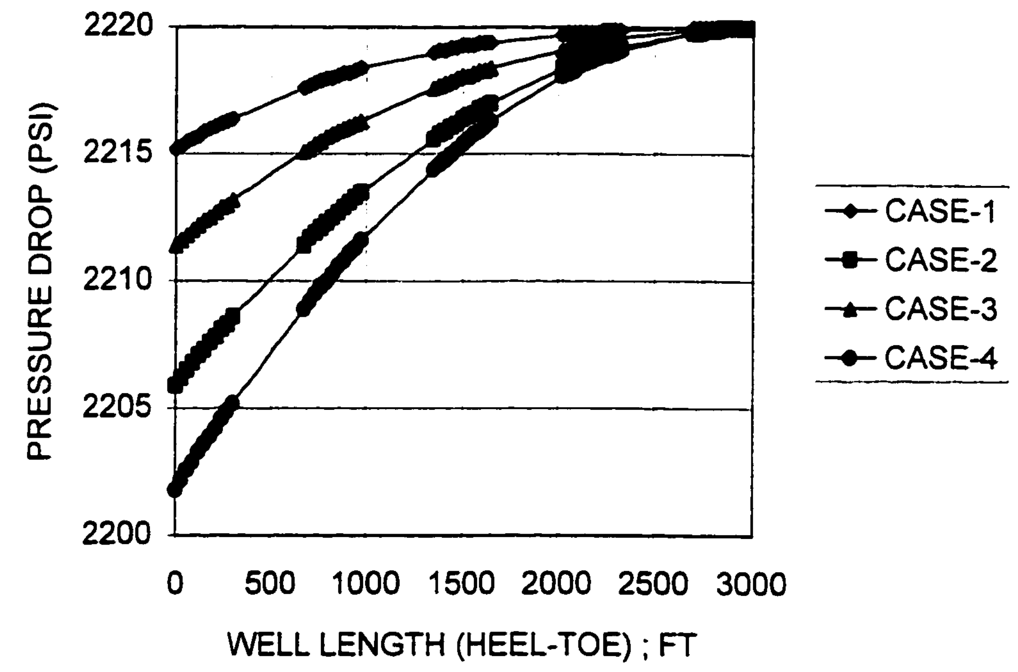

Figure 8.14: Pressure Profiles with Different Cases for LD=0.75 & Dia.=0.5ft

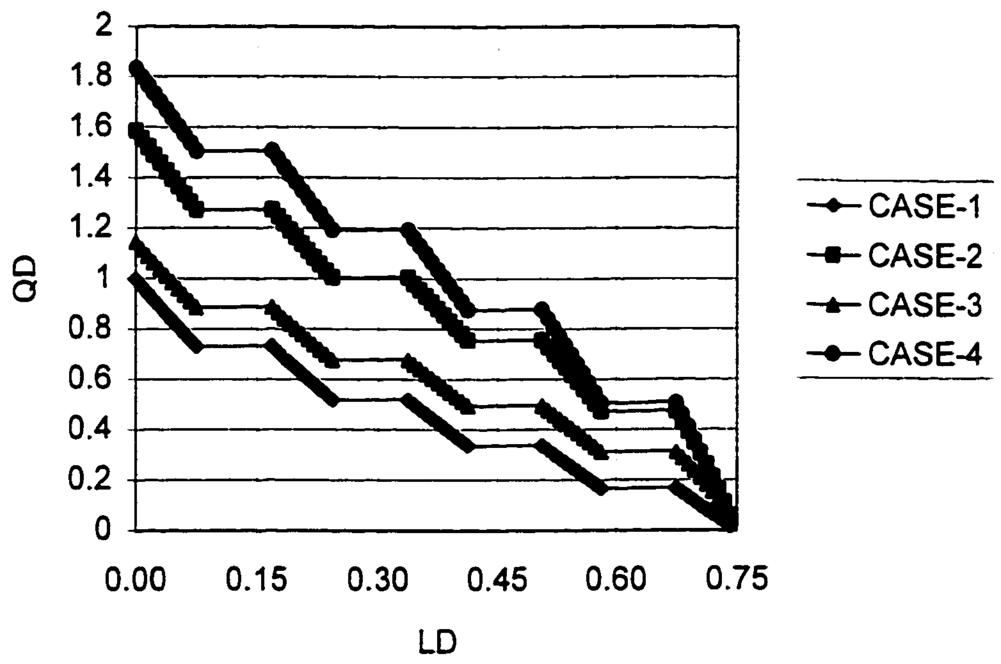

Figure 8.15: Well Performance with Different Cases for LD=0.75 & Dia=0.375ft

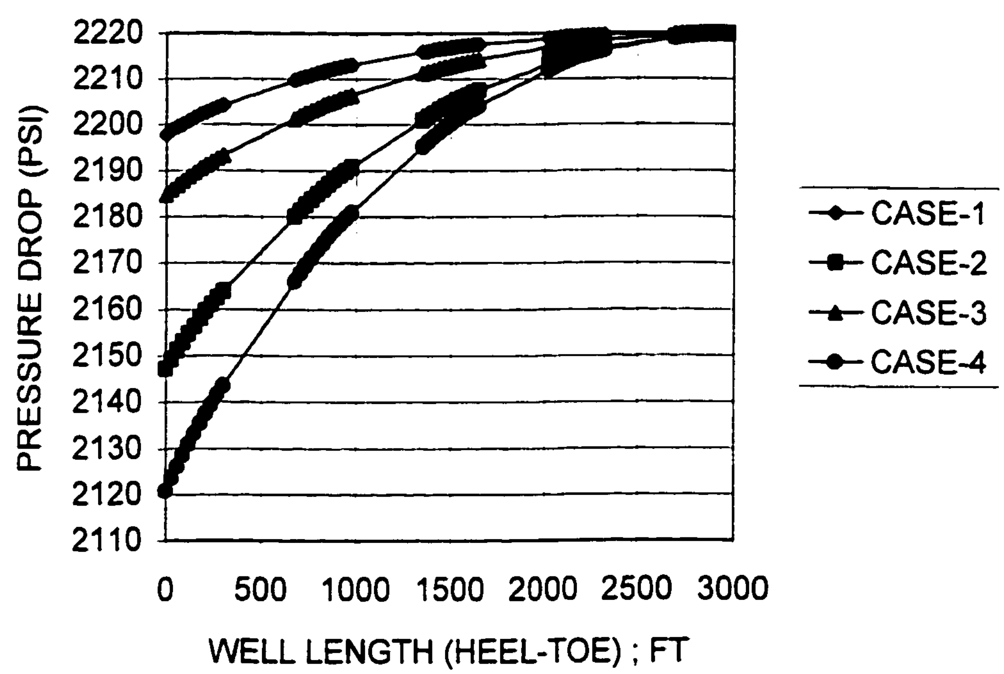

Figure 8.16: Pressure Profiles with Different Cases for LD=0.75 & Dia.=0.375ft

Following comments can be made regarding the exercise:

- Different skin profiles give different results. For a well of 1000ft and 6inches diameter (Figure 8.3) the flow performances are not similar and a difference of 25% can be seen between case-1 and case-4 profiles. The results are almost similar for 4.5 inches of diameter. However the curves with skin profiles of case-2 and case-4 perform closely (see Figure 8.5) with each other and this seem related with nearly similar pressure drop associated with these cases. See Figure 8.6.

- When a well of 2000ft and 6inches diameter is considered. the flow performances seem far from identical. The difference between case-1 and case-4 skin profiles extends to 40% (Figure 8.8). Similarly when higher frictional forces are encountered in 4.5 inches diameter well, the performances get further apart and case-4 gives approximately 45% more performance than case-1. See Figure 8.10.

- The results reported till Figure 8.11 successively confirm the fact that the higher the well length and frictional forces, the higher the difference in flow rates between the case where the skin is assumed constant compared with more realistic steeper profile. This fact is confirmed when performance for 3000ft well with diameters of 6 and 4.5 inches are evaluated. See figures 8.13

and 8.15. It has been shown that performances can differ by 60% to 80% when encountering higher frictional forces. This means that if for such wells, constant skin of 24 is considered instead of a real skin varying from 60 to zero, (Figure 8.12) the flow rate performance are under evaluated by a factor of even 1.8 though the average skin is 24 for both the cases.

8.3 Well Performance after Stimulation

In this section the next sets of experiments are performed and the well performances are estimated under different condition of stimulation.

8.3.1 Successive Damage Removal of whole well

First a skin profile is estimated using Yan's approach [7]. Four cases of stimulation are assumed. In the first case it is assumed that only 25% of the formation damage is removed and in the fourth case all the damage is removed. See Figure 8.17. The results presented in Figure 8.18 show as expected that, the more damage removed the better the performance. More importantly, Figure 8.18 shows that the last 25% of the damage to be removed are responsible for more production loss than the first 75% of the formation damage. These effects are more pronounced when we consider higher frictional losses as shown in Figure 8.19. In other words, even a small formation damage level can cost significant production loss to the well and an incomplete stimulation job will barely recover the full potential of the well.

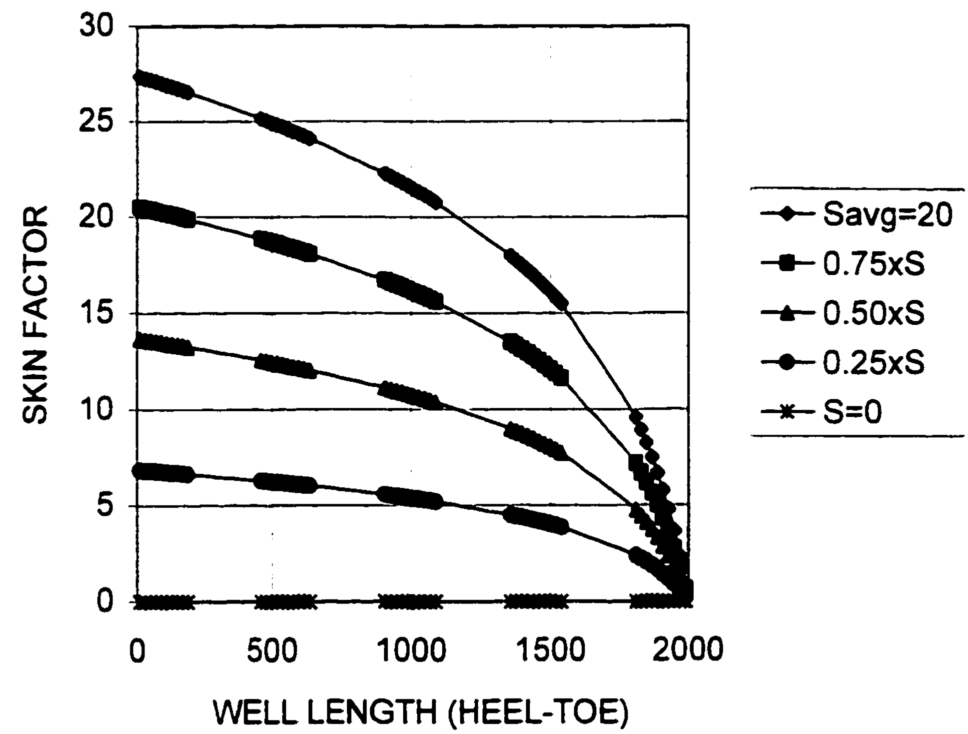

Figure 8.17: Decreasing skin profiles for L=2000ft.

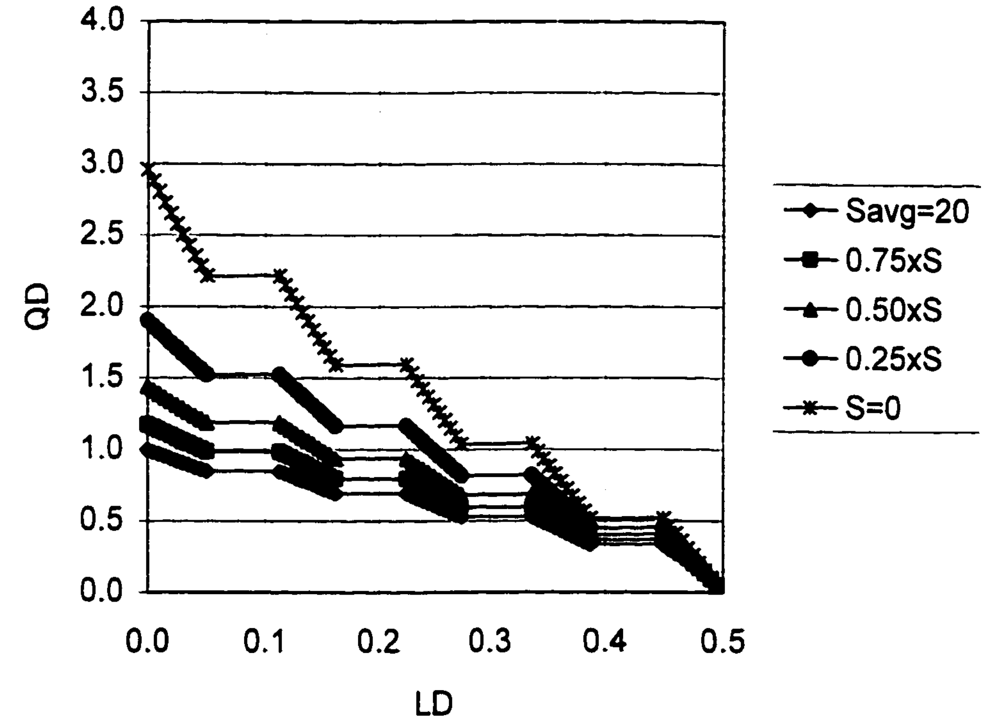

Figure 8.18: Well performance after successive damage removal with Dia=0.5ft and LD=0.5

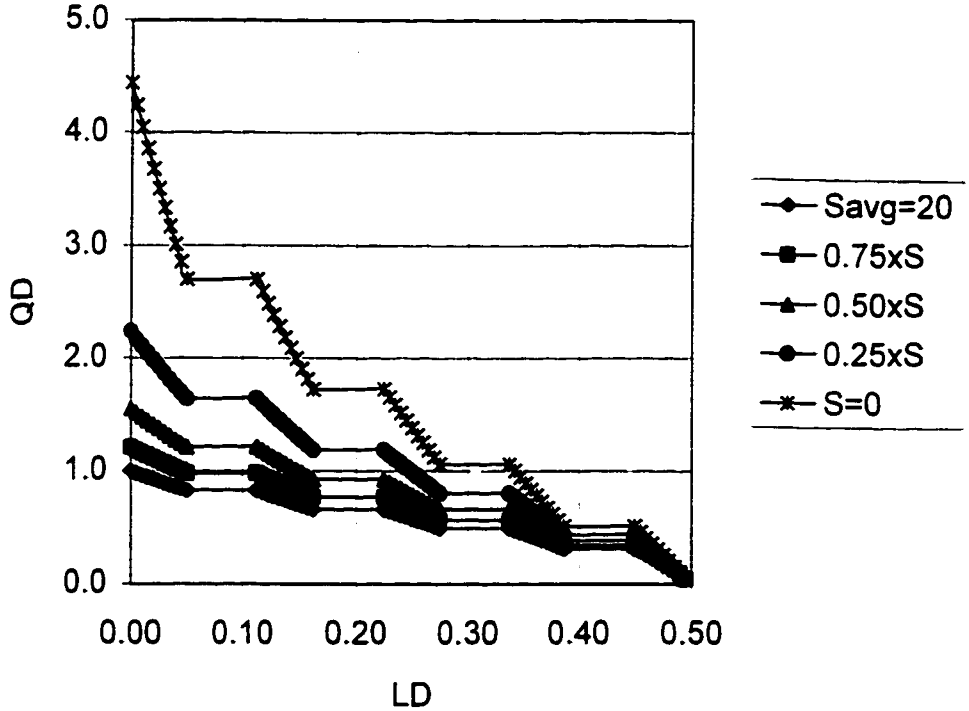

Figure 8.19: Well performance after successive damage removal with Dia=0.375ft and LD=0.5

8.3.2 Well Stimulation at Heel and Toe

In this sub-section of well stimulation we investigate, that whether stimulation at well heel or well toe is beneficial in obtaining the maximum well performance. The stimulation of the section closest to heel and toe is considered only for given PCHW.

In the skin profile represented by case-2, which correspond to a linear decrease, removing skin from the area near the heel, results as expected in more production gain than removing the damage from the area near the toe. This is especially true if the friction forces are not very important. For example, Figure 8-21 shows an increment of approximately 40% when stimulation at the well heel is considered. While almost constant performance is obtained from the similar stimulation of at the well toe (Figure 8-20).

However the same may not be true when a constant skin profile as depicted in case-1 is considered along with well length of 3000ft and diameter of 4.5 inches. As shown in Figures 8-22 and 8-23, stimulating the area near the toe in a 3000ft well results in a production gain of almost 100% than compared with a gain of 75%, when stimulation near the heel is considered.

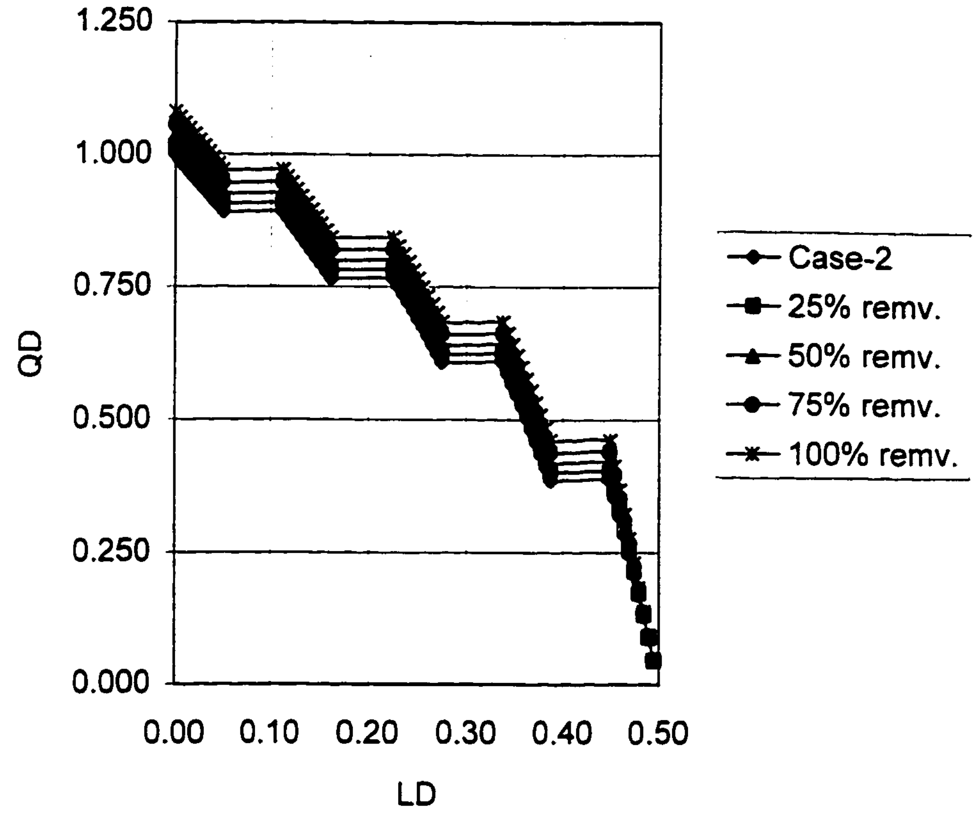

Figure 8-20: Successive damage removal at Toe with Case-2 profile For LD=0.5 and Dia=0.5ft.

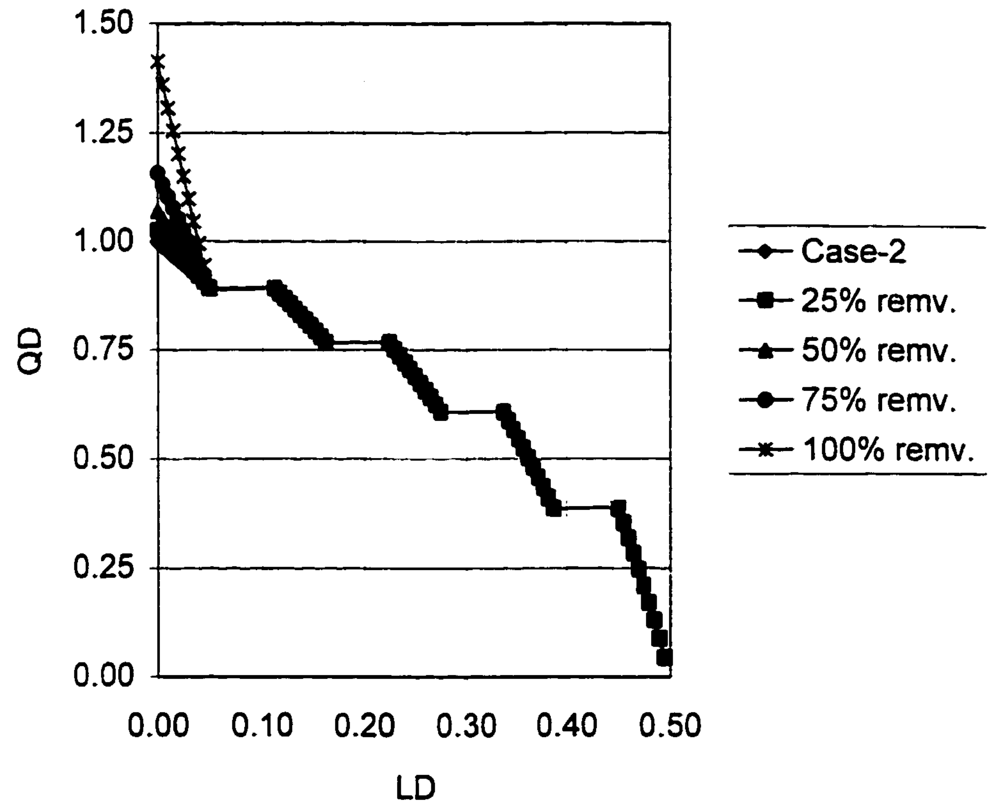

Figure 8-21: Successive damage removal at Heel with Case-2 profile
For LD=0.5 and Dia=0.5ft.

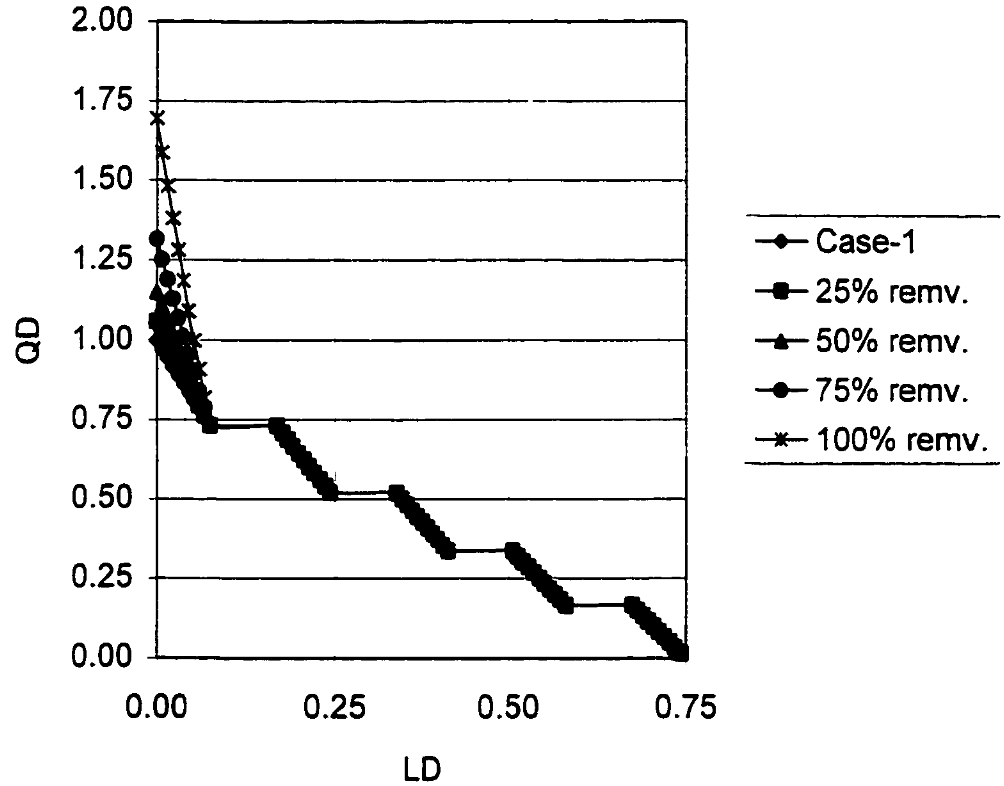

Figure 8-22: Successive damage removal at Heel with Case-1 profile For LD=0.75 and Dia=0.375ft.

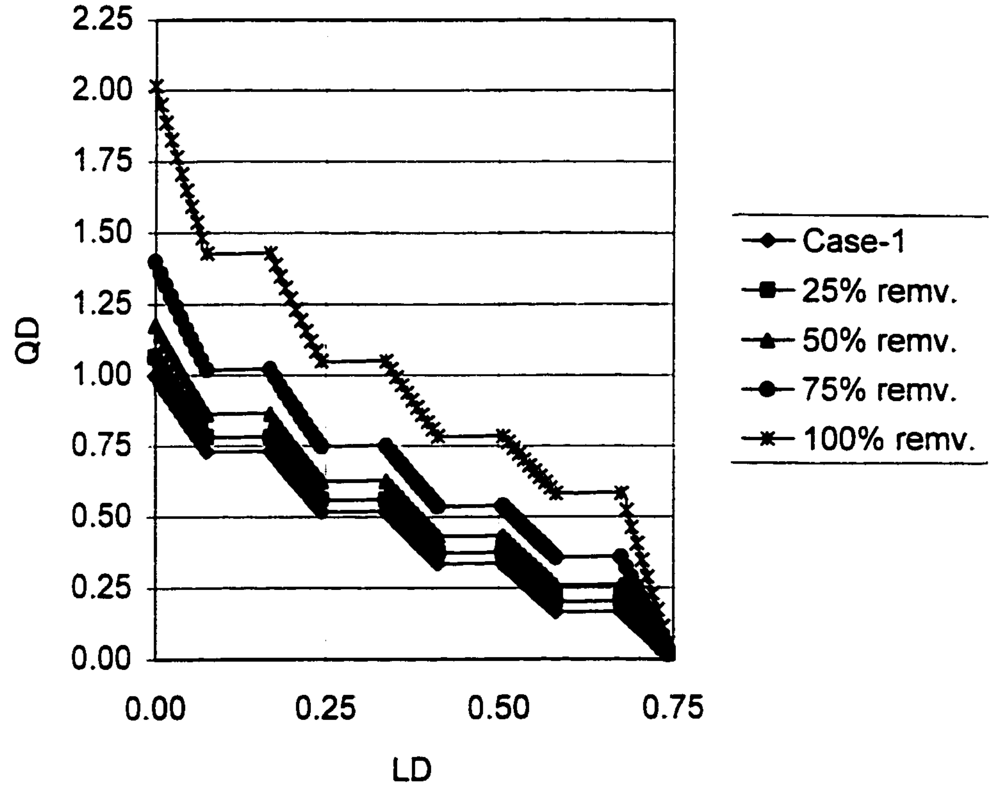

Figure 8-23: Successive damage removal at Toe with Case-1profile
For LD=0.75 and Dia=0.375ft.

8.4 EFFECT OF RESERVOIR HEIGHT WITH VARIOUS DEGREES OF DAMAGE ON WELL PERFORMANCE

In this section we intend to investigate the effect of reservoir height and well open percentage, with especial emphasis on the effect of various degrees of formation damage, on the horizontal well performance.

Here we have plotted well open percentage, which is varied from 20%, to 100% against various degree of formation damage. To investigate the effect of height, the dimensionless reservoir heights, HD of 0.005, 0.01, 0.015, 0.02 and 0.025 are used for LD=0.25. These plots are shown from Figures 8-24 to 8-28.

Similarly, the same sets of experiments are repeated for LD=0.5 and LD=0.75. The figures are plotted from Figure 8-29 to 8-38. The data in terms of rate (bbl/day) at the heel, is computed with dimensionless lengths of LD=0.25, 0.5 and 0.75. This is presented from Table 8-2 to 8-4 respectively.

The effect of reservoir height on the flow performance of PCHW is evaluated here with varying degree of well open percentage and different levels of skin. The results obtained from the model are shown in Table 8-2 and plotted through Figures 8-24 to 8-28, for LD=0.25.

Figure 8-24 shows the effect of change in the well open percentage with various levels of skins, for LD=0.25 and HD=0.005. The well open percentage is increased from 20% to 100% (open hole). Four different levels of skin are used here to investigate the effect of various degree of damage on the horizontal well performance. The first level corresponds to zero skin, the second level represents 50% decrease in skin from the base case which is the third level of skin. In the fourth level 50% increment in the skin of the base case is considered.

It can be seen from Figure 8-24, that for LD=0.25 and HD=0.005 (which is relatively a case of shorter well in thin reservoir) even 20% open PCHW can perform upto 75% when compare with open hole (100% open) for S=0.

Further Figure 8-24 shows that an increase in the level of skin yields lower performances. At lower levels of skin, especially at S=0, the decrease in the performance is more momentous below 40% PCHW. Higher levels of skin exhibit almost similar behavior.

Figure 8-25 shows the case, when HD=0.01, with other parameters similar to ones employed in Figure 8-24. It is evident here that at S=0, the curve exhibit somewhat differently from the curves at higher levels of skins. The performance at S=0 is proportionally higher than the performance increment among higher levels of skins.

With respect to well open percentage, the decline in the performance of PCHW for S=0 is evident from the beginning.

Generally with the case of thin reservoirs and shorter well lengths, PCHW perform comparative with open hole wells. Hence in these cases, a reduction in the well open percentage can be sustained without a significant loss in performance. However as the reservoir height is increased, this effect is minimized and the relative performance of PCHW with open hole well becomes lesser and lesser. Figures 8-26. 8-27 and 8-28 plotted for HD=0.015, 0.020 and 0.025 respectively, conform with the above discussion.

The effect of various levels of skins is also noticeable here. It is apparent that as the reservoir height is increased, the performance curve of PCHW with S=0. separates to higher performances than horizontal wells with higher level of skins. At higher levels of skin, the performance curves get closer and closer. This is in agreement with the fact that even lesser degree of formation damage substantially reduces the well performance; and the effect is more pronounced, when higher frictional pressure drop is expected. See Figures 8-24 to 8-28

Table 8.2: Horizontal Well Performance (bbl/day), with Variation in HD, Well Open Percentage and Skin for LD=0.25

HD=0.005	20%	40%	60%	80%	100%
S=0	3893	4667	5023	5185	5206
S=7	2489	3418	3946	4261	4420
S=14	1913	2751	3286	3642	3856
S=21	1588	2328	2834	3194	3430
HD=0.01	20%	40%	60%	80%	100%
S=0	5962	7927	8984	9567	9788
S=7	3263	4937	6062	6842	7332
S=14	2400	3716	4681	5412	5924
S=21	1952	3029	3856	4513	4996
HD=0.015	20%	40%	60%	80%	100%
S=0	7157	10237	12128	13301	13860
S=7	3629	5777	7363	8560	9384
S=14	2625	4212	5457	6461	7211
S=21	2118	3378	4395	5245	5898
HD=0.02	20%	40%	60%	80%	100%
S=0	7919	11928	14661	16514	17504
S=7	3840	6302	8234	9777	10899
S=14	2753	4511	5948	7154	8085
S=21	2212	3585	4728	5712	6482
HD=0.025	20%	40%	60%	80%	100%
S=0	8443	13205	16727	19295	20774
S=7	3976	6658	8854	10678	12054
S=14	2835	4710	6285	7643	8713
S=21	2273	3722	4952	6033	6889

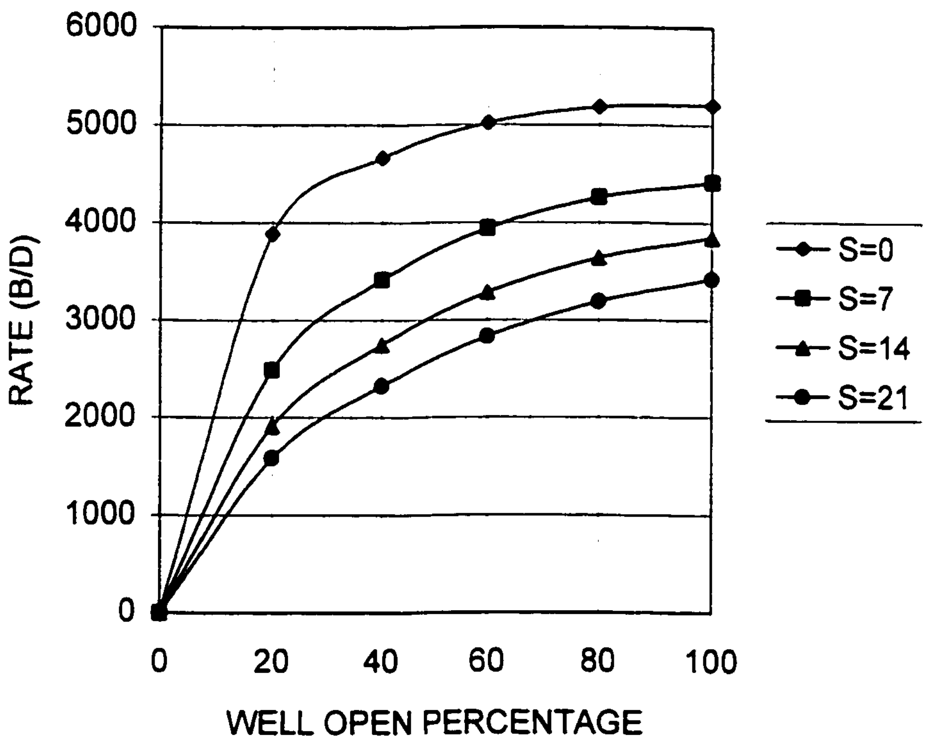

Figure 8-24: Well Performance with LD=0.25 and HD=0.005

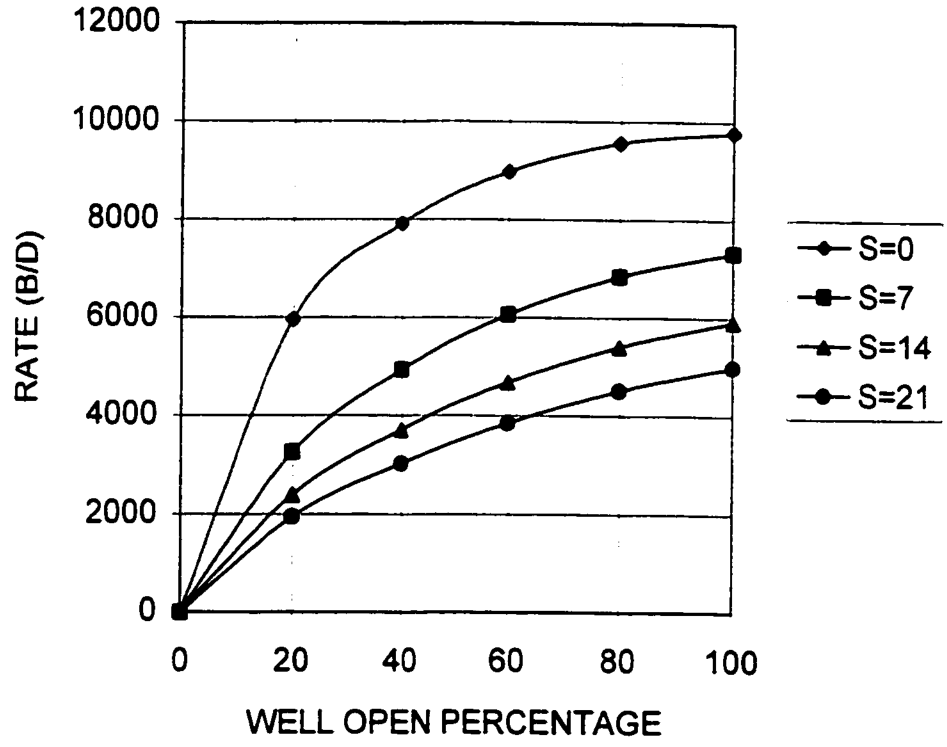

Figure 8-25: Well Performance with LD=0.25 and HD=0.01

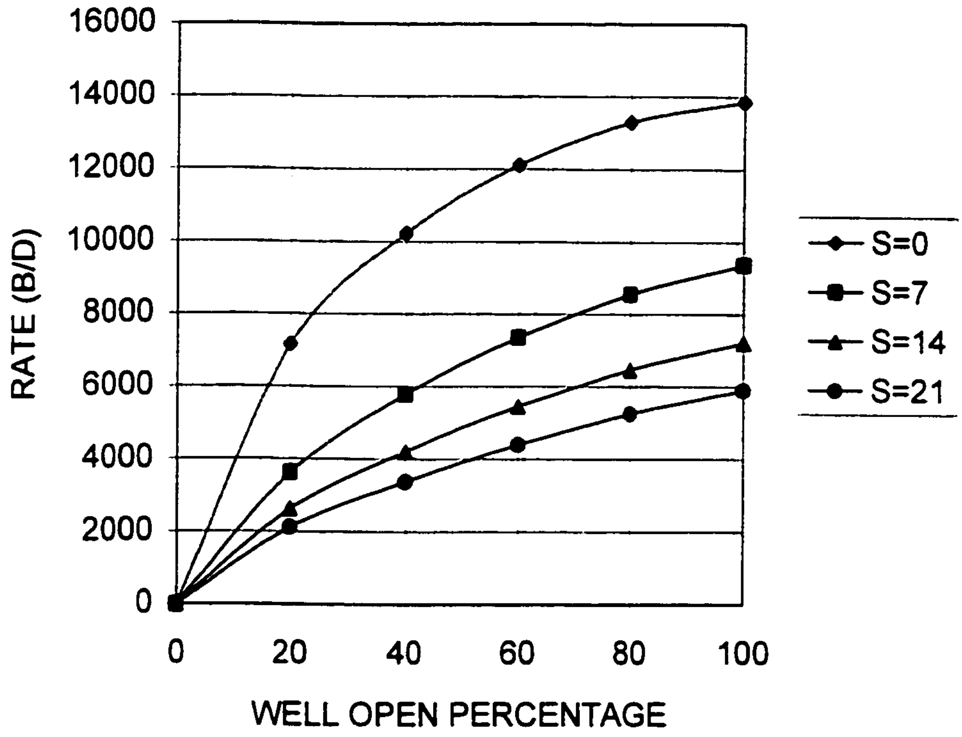

Figure 8-26: Well Performance with LD=0.25 and HD=0.015

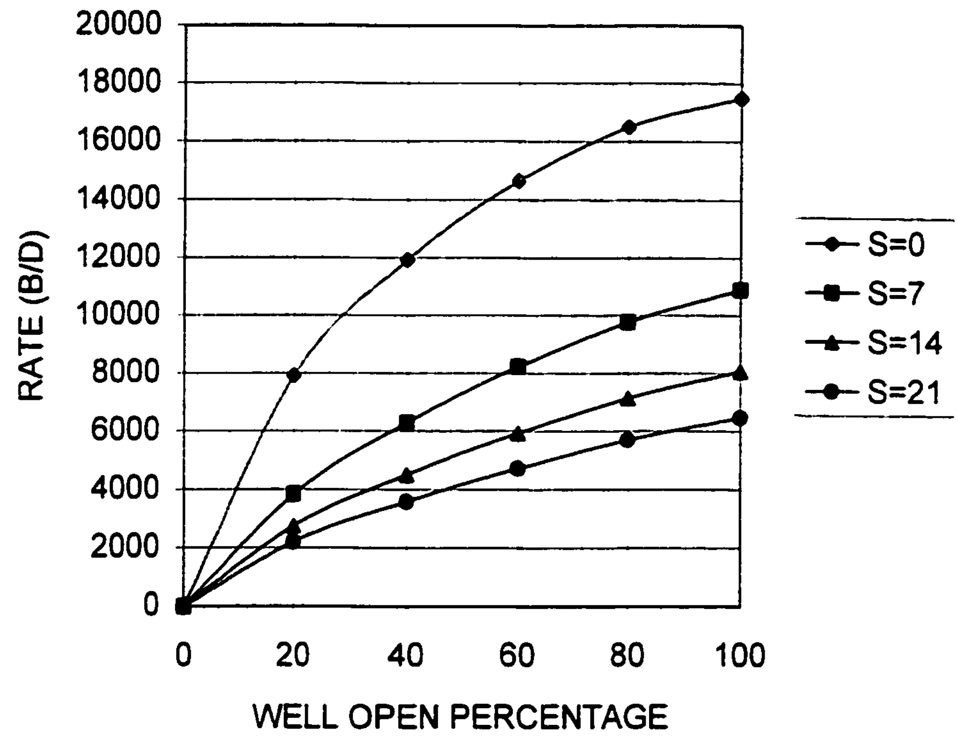

Figure 8-27: Well Performance with LD=0.25 and HD=0.02

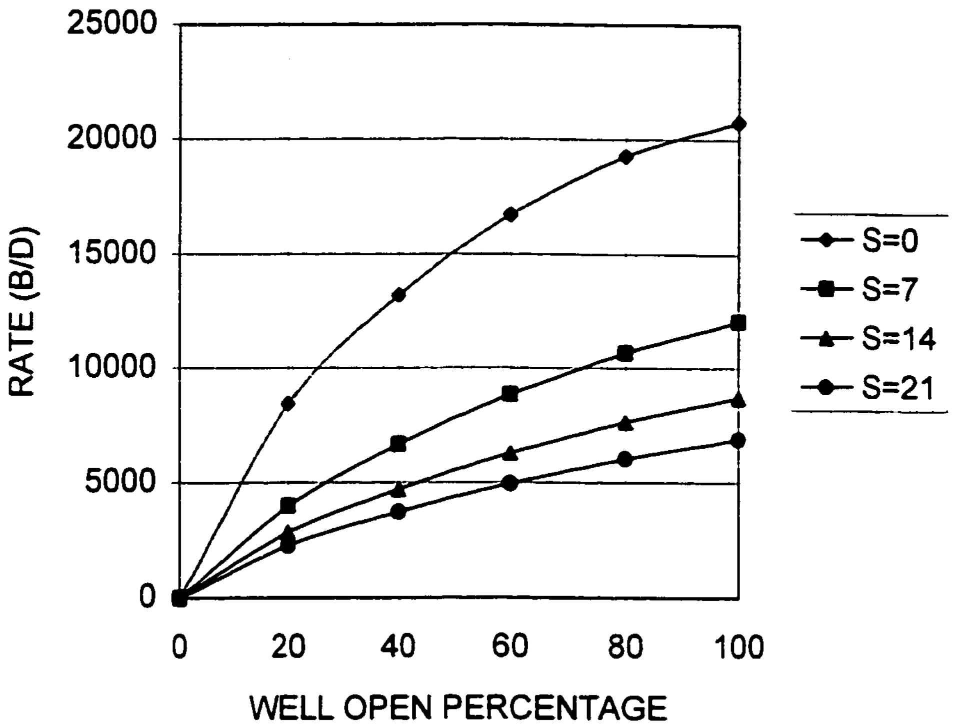

Figure 8-28: Well Performance with LD=0.25 and HD=0.025

8.5 EFFECT OF RESERVOIR LENGTH WITH VARIOUS DEGREES OF DAMAGE

To investigate the effect of length. similar experiments are repeated here (as shown earlier in section 8-4) with LD=0.50. The results are plotted from Figures 8-29 to 8-33 and the data is presented in Table 8.3.

Figure 8.29 is plotted with LD=0.5 and HD=0.005 for different levels of skins. The performance of PCHW is significantly higher when the PCHW is above 60% open for S=0. However the performance goes down rapidly as the open percentage is decreased from 60%.

As the various levels of skins are examined, it can be seen that the performance is effected negatively by the increase in the level of skin. Also the decrease in the performance of PCHW is more evident from the beginning with the decrease in the well open percentage at higher levels of skins than at S=0. See Figure 8.29.

From Figures 8-30 to 8-33, the reservoir height is successively increased from HD=0.01 to 0.025 respectively. Figure 8-30 plotted with HD=0.01 shows almost the same trends as discussed earlier in the Figure 8-29. However, the performance curve with S=0 separates, more visibly than the curves representing higher levels of damage.

Table 8.3: Horizontal Well Performance (bbl/day), with Variation in HD, Well Open Percentage and Skin for LD=0.50

HD=0.005	20%	40%	60%	80%	100%
S=0	7316	9386	10570	11058	10895
S=10	4288	6269	7585	8397	8677
S=20	3182	4824	6008	6841	7258
S=30	2584	3968	5016	5806	6261
HD=0.01	20%	40%	60%	80%	100%
S=0	12019	17958	22420	24353	24424
S=10	5644	9172	12046	14081	15224
S=20	3964	6455	8538	10184	11277
S=30	3138	5072	6713	8077	9036
HD=0.015	20%	40%	60%	80%	100%
S=0	15113	25917	36491	41963	43321
S=10	6286	10847	15064	18359	20607
S=20	4318	7289	9971	12235	13916
S=30	3383	5608	7598	9334	10643
HD=0.02	20%	40%	60%	80%	100%
S=0	17216	33106	52728	65305	70182
S=10	6649	11919	17226	21697	25120
S=20	4512	7788	10889	13623	15782
S=30	3517	5921	8139	10133	11689
HD=0.025	20%	40%	60%	80%	100%
S=0	18699	39441	70720	95572	107882
S=10	6875	12651	18834	24351	28927
S=20	4633	8115	11523	14619	17164
S=30	3599	6122	8501	10683	12420

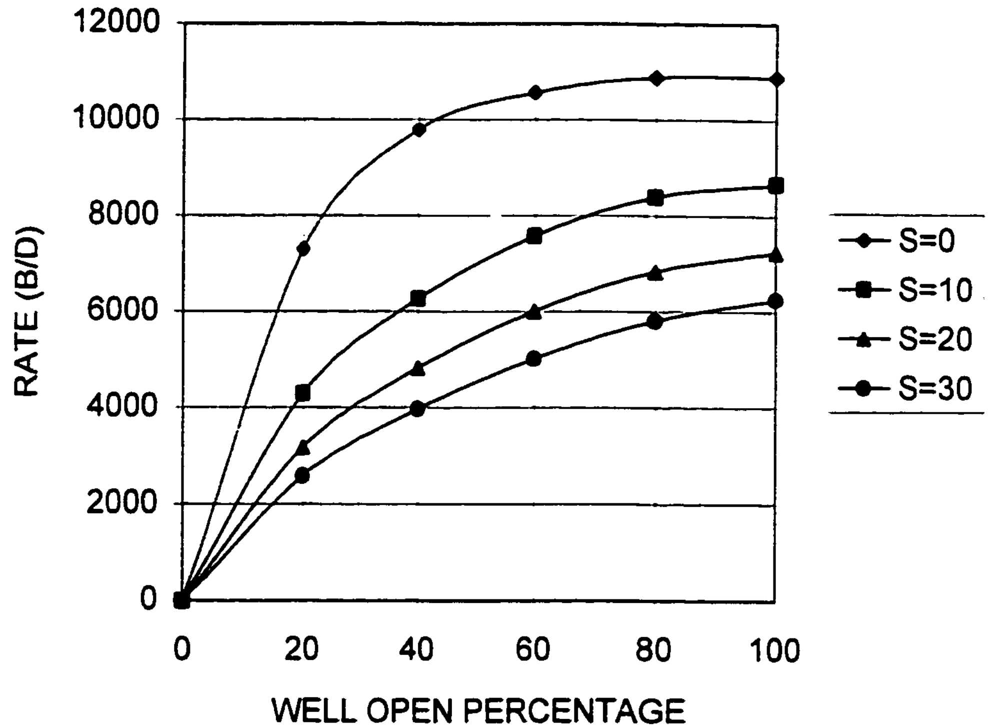

Figure 8-29: Well Performance with LD=0.50 and HD=0.005

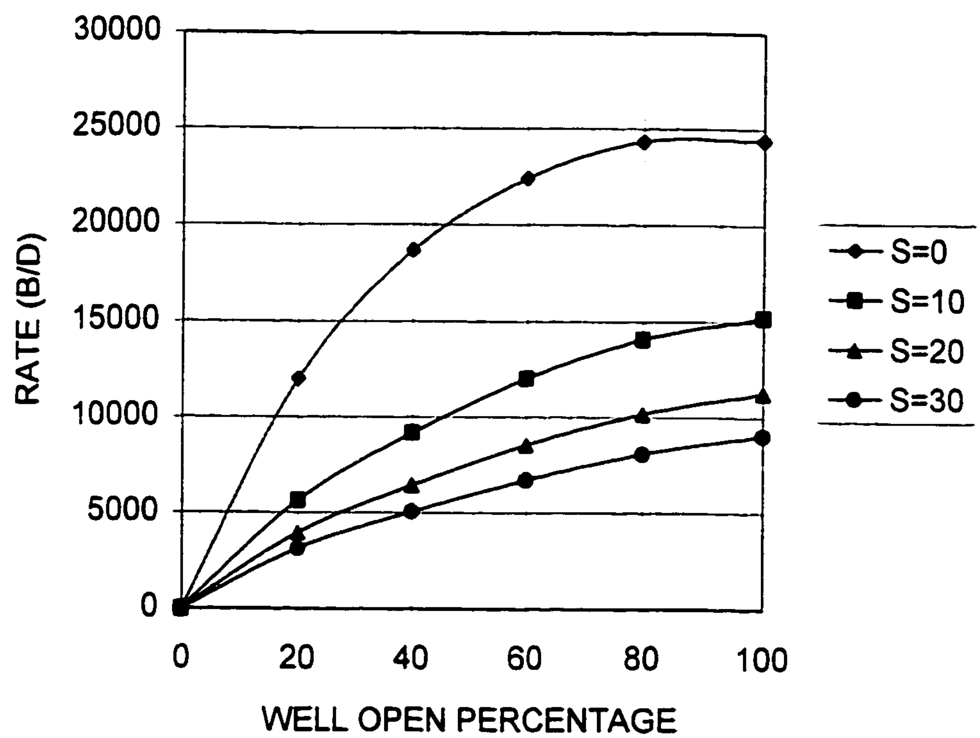

Figure 8-30: Well Performance with LD=0.50 and HD=0.01

Generally with the increase in reservoir height and length, well productivity also increases. However even lower degrees of formation damage in these cases curtail much of the productivity and the influence of degree of damage is more pronounced, than the wells with lower productivities. This is evident in Figure 8-31 where well with LD=0.5 and HD=0.015, shows a marked difference in performance with S=0 to other higher levels of skins. As the degree of damage increases the performance curves get closer and closer. These effects are more pronounced with HD=0.02 and HD=0.025, plotted in Figures 8-32 and 8-33 for LD=0.5

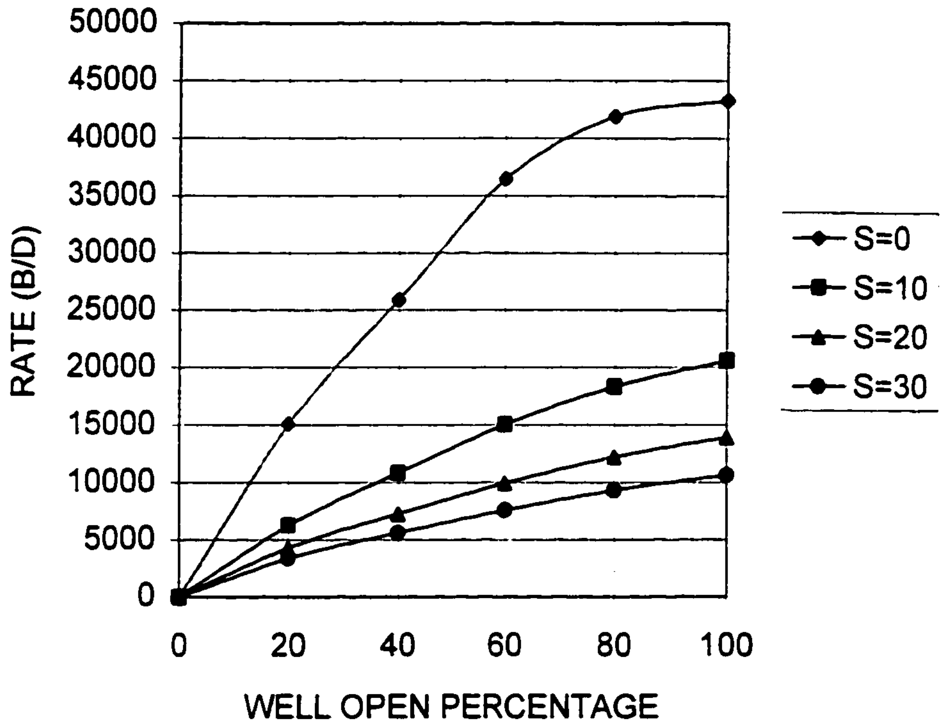

Figure 8-31: Well Performance with LD=0.50 and HD=0.015

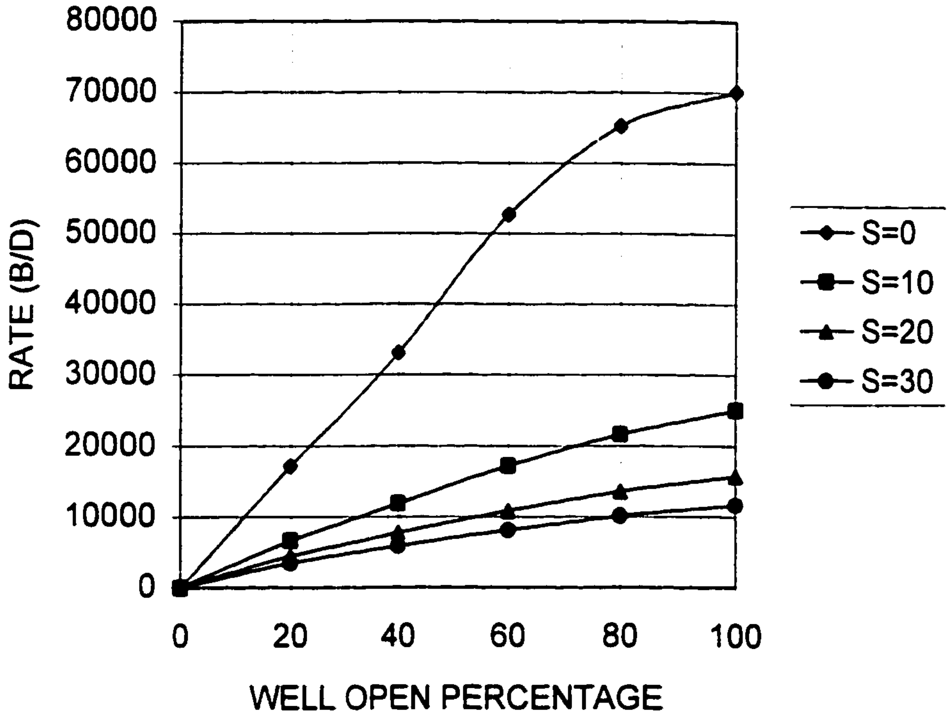

Figure 8-32: Well Performance with LD=0.50 and HD=0.02

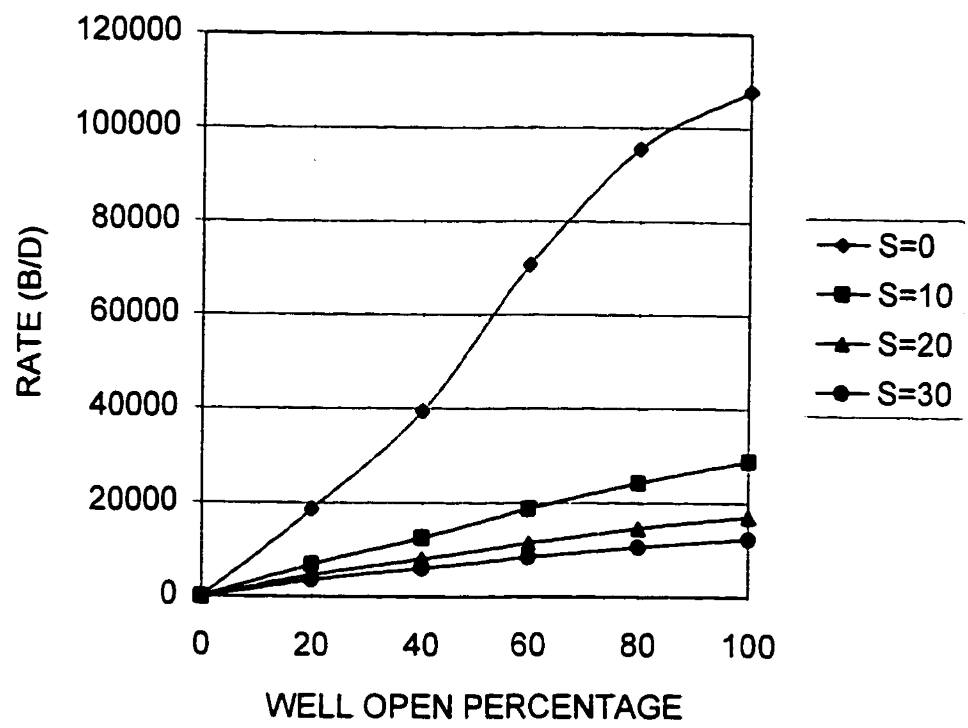

Figure 8-33: Well Performance with LD=0.50 and HD=0.025

The sets of experiments performed with LD=0.25 and LD=0.5 are repeated here LD=0.75. The data is presented here in Table 8.4 and plotted through Figures 8-34 to 8-38.

In Figure 8-34, for S=0 the performance curve with S=0, goes rapidly down below 80% open PCHW. In this case the feasibility aspect of PCHW comes in question when compared with open hole well. For example a 20% open well here with LD=0.75 and HD=0.005 shows a performance of 43% compared with open hole well with open hole well. This is much lower than the performance of 20% open well having 75% performance, compared with open hole well with LD=0.25 and HD=0.005 (see Figure 8-24). These factors are successively more pronounced with the increase in reservoir height as shown through Figures 8-35 to 8-38. Also evident is the fact that with no skin (S=0) and LD=0.75 (L_w=3000tf), the performance rises very rapidly. In fact this represents only theoretical aspect. In practical case a certain degree of damage is always present and influence at a greater extent with even lower values; than damage at the higher levels where performance curves merge closer. Hence after a certain high level of damage the performance is not momentously affected by the increase in the damage level.

Table 8.4: Horizontal Well Performance (bbl/day), with Variation in HD, Well Open Percentage and Skin for LD=0.75

HD=0.005	20%	40%	60%	80%	100%
S=0	12183	18930	24718	28000	28464
S=12	6304	10423	14047	16917	18212
S=24	4494	7458	10087	12288	13585
S=36	3571	5900	7976	9760	10924
HD=0.01	20%	40%	60%	80%	100%
S=0	23182	51967	96048	149423	152114
S=12	8397	15943	24491	33474	39452
S=24	5575	9971	14496	19021	22406
S=36	4292	7433	10527	13547	15851
HD=0.015	20%	40%	60%	80%	100%
S=0	32438	107867	-	-	-
S=12	9412	19406	32741	49874	64206
S=24	6058	11265	17066	23480	28847
S=36	4604	8161	11838	15661	18756
HD=0.02	20%	40%	60%	80%	100%
S=0	39712	-	-	-	-
S=12	9984	21711	39197	65256	90918
S=24	6319	12034	18724	26611	33668
S=36	4770	8578	12626	17001	20651
HD=0.025	20%	40%	60%	80%	100%
S=0	45269	-	-	-	-
S=12	10338	23310	44245	79172	118126
S=24	6476	12532	19861	28896	37349
S=36	4870	8840	13144	17917	21967

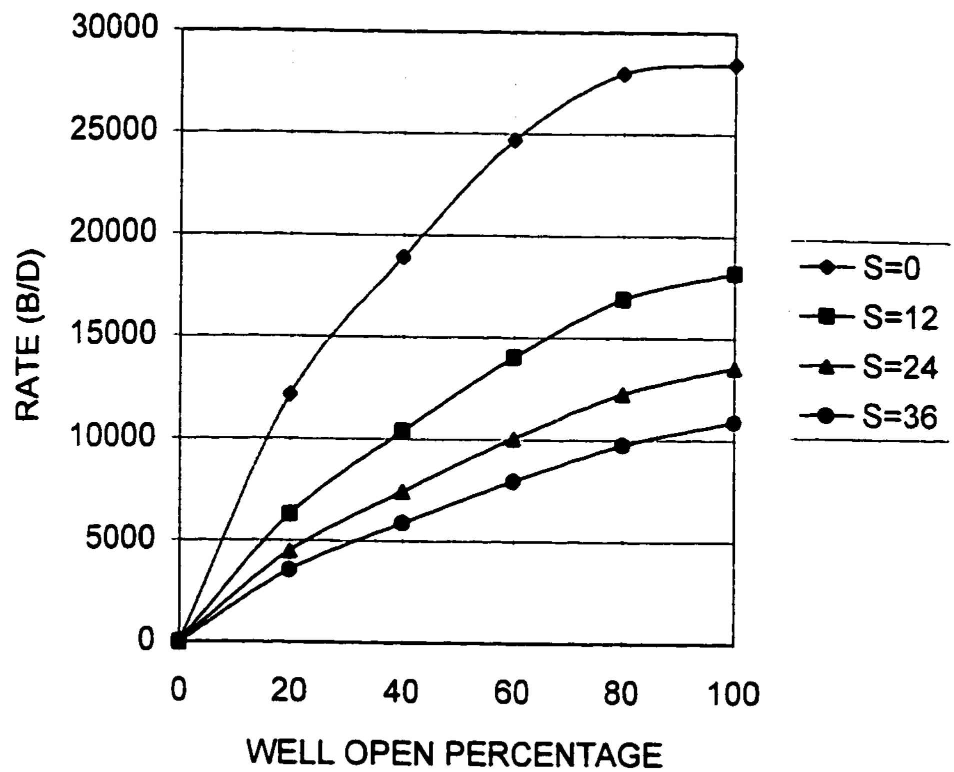

Figure 8-34: Well Performance with LD=0.75 and HD=0.005

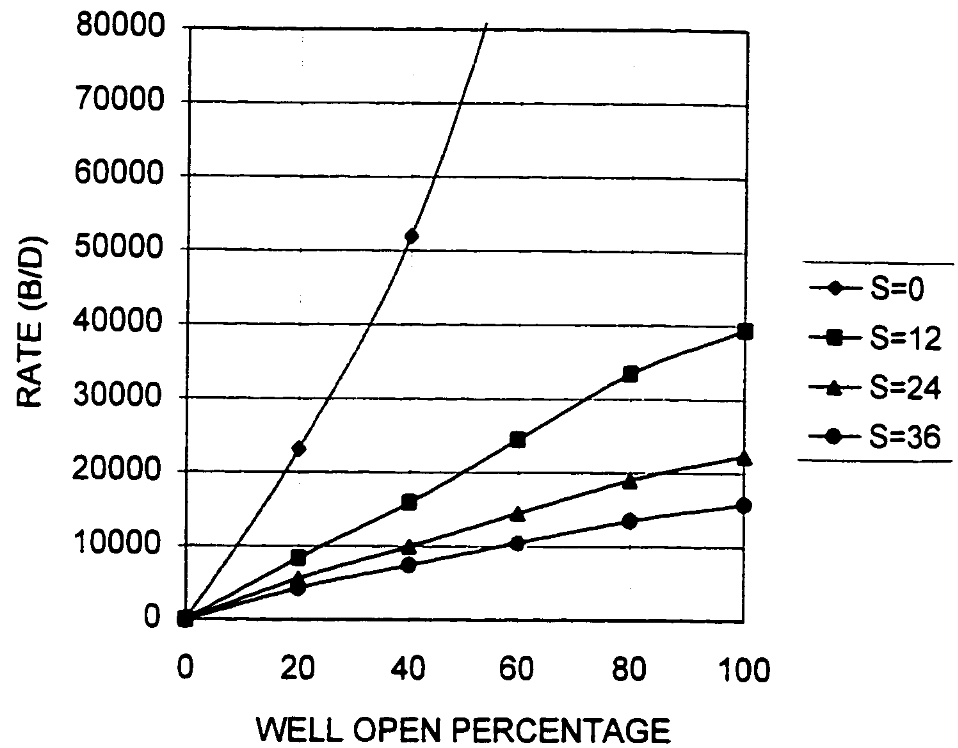

Figure 8-35: Well Performance with LD=0.75 and HD=0.01

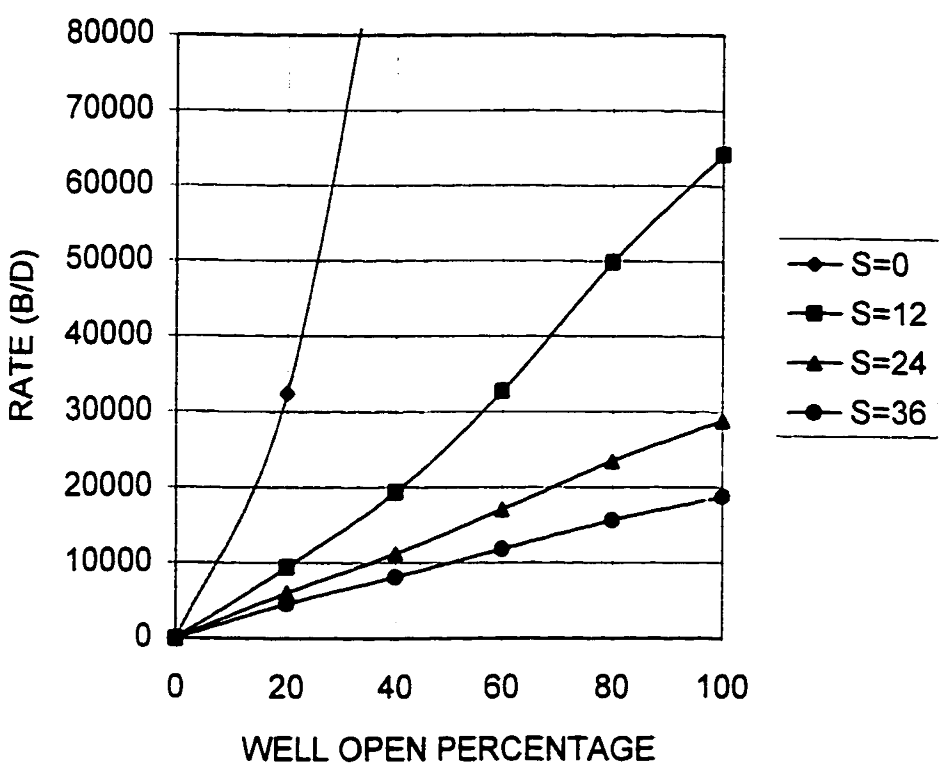

Figure 8-36: Well Performance with LD=0.75 and HD=0.015

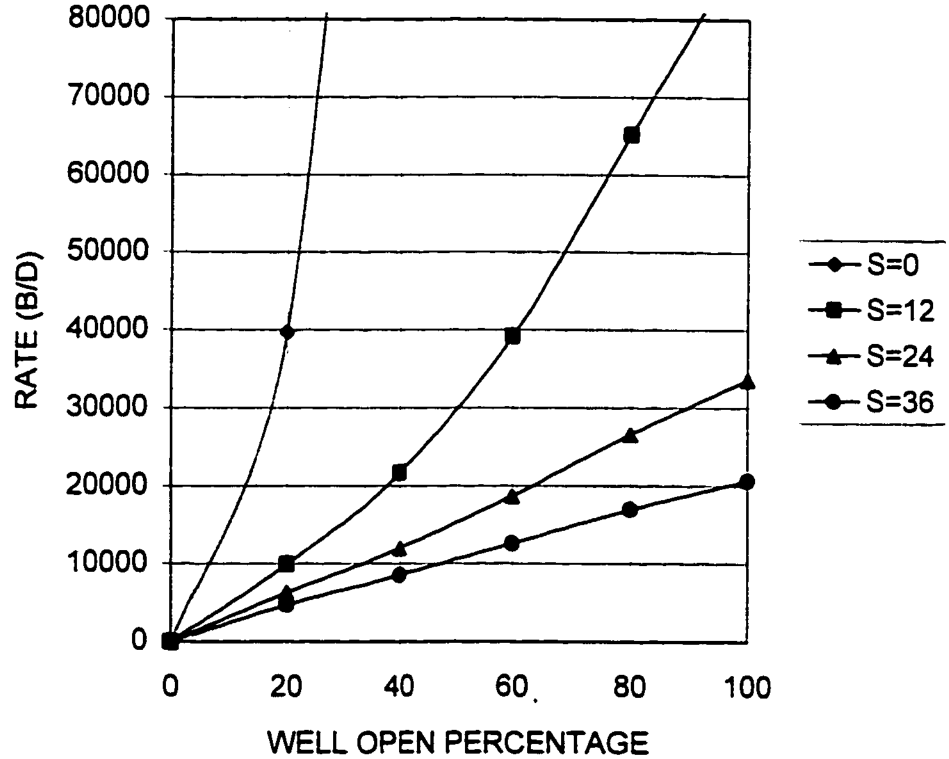

Figure 8-37: Well Performance with LD=0.75 and HD=0.02

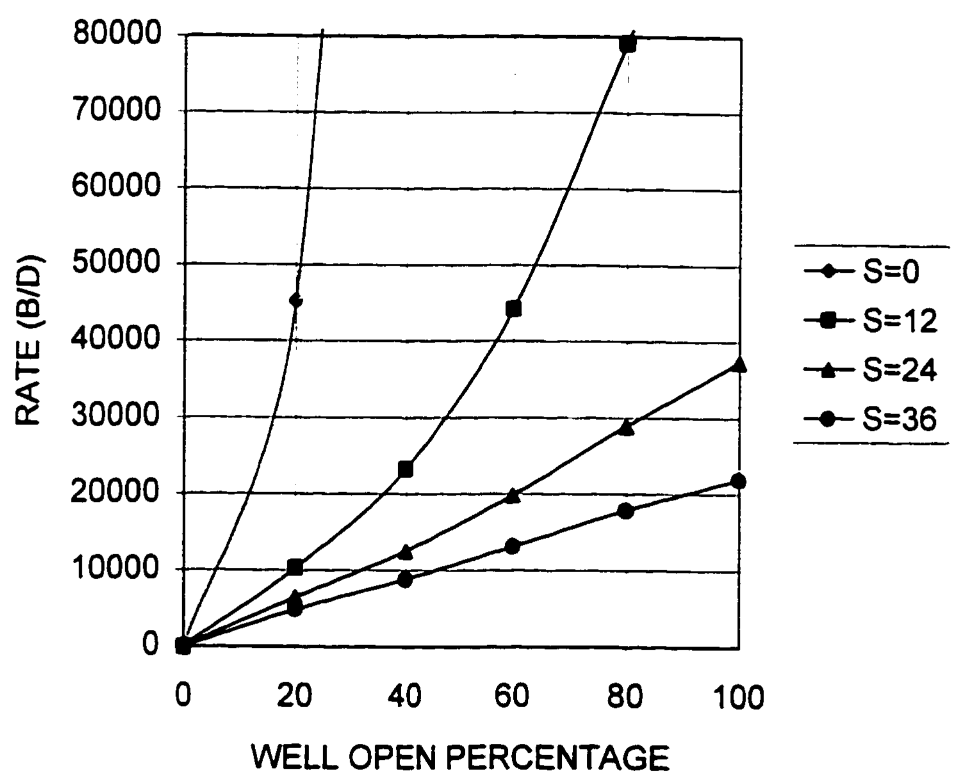

Figure 8-38: Well Performance with LD=0.75 and HD=0.025

8.6 Effect of Reservoir Anisotropy

In this section we have evaluated the effect of reservoir anisotropy on the performance of PCHW over varying nature and degree of damage. Effect of reservoir height and reservoir length has also been evaluated in this respect.

Anisotropy defined as ratio of k_h/k_v, is varied, by varying vertical permeability only, while keeping $k_x = k_y = 2500$md, as constant. Anisotropy variation is taken from 1 to 10. The ratio of 1 represents isotropic case.

8.6.1 Comparative Effect of Different Skin Profiles

In this sub section we intend to evaluate the relative effect of different skin profiles with the variation in the reservoir anisotropy on the performance of PCHW. The data is presented in Table 8-5 and plotted through Figures 8-39 to 8-41

Figure 8-39 is plotted with HD=0.02 and LD=0.25 for case-2 profile, which decreases linearly from well heel to toe. Well performance is plotted against the anisotropy variation with various degrees of formation damage. Figure 8-39 shows the effect of reservoir anisotropy on the well performance. As the anisotropy increases the performance goes down and this seems irrespective of the degree of damage. However the curve with S=0 performs, better than the curves representing higher degrees of damage. As the degree of damage increases the performance curves get closer and closer. This shows that even lower skins, markedly reduce the well performance.

Table 8.5: Horizontal Well Performance (bbls/day) with change in Anisotrpy Ratio for Case-2 Profile

LD=0.25 ; HD=0.02 ; CASE-2				
Kh/Kv	S=0	S=7	S=14	S=21
1	16620	10791	8444	7107
2	14195	8723	6718	5610
3	12795	7629	5828	4848
4	11830	6909	5251	4357
5	11104	6386	4835	4004
6	10528	5980	4514	3733
7	10054	5652	4257	3516
8	9654	5380	4043	3337
9	9310	5149	3863	3185
10	9009	4949	3707	3054
LD=0.50 ; HD=0.02 ; CASE-2				
Kh/Kv	S=0	S=10	S=20	S=30
1	63642	24921	16958	13365
2	46077	18204	12603	10029
3	37989	15182	10603	8473
4	33123	13360	9379	7514
5	29795	12104	8528	6842
6	27340	11169	7889	6336
7	25434	10436	7385	5936
8	23899	9841	6974	5608
9	22628	9345	6630	5334
10	21556	8923	6336	5099
LD=0.75 ; HD=0.02 ; CASE-2				
Kh/Kv	S=0	S=12	S=24	S=36
1	-	89006	39817	26575
2	-	45754	24308	17408
3	-	33031	18850	13902
4	-	26780	15920	11938
5	-	22991	14040	10643
6	-	20413	12707	9706
7	-	18526	11700	8989
8	-	17074	10906	8416
9	-	15915	10259	7945
10	-	14963	9718	7548

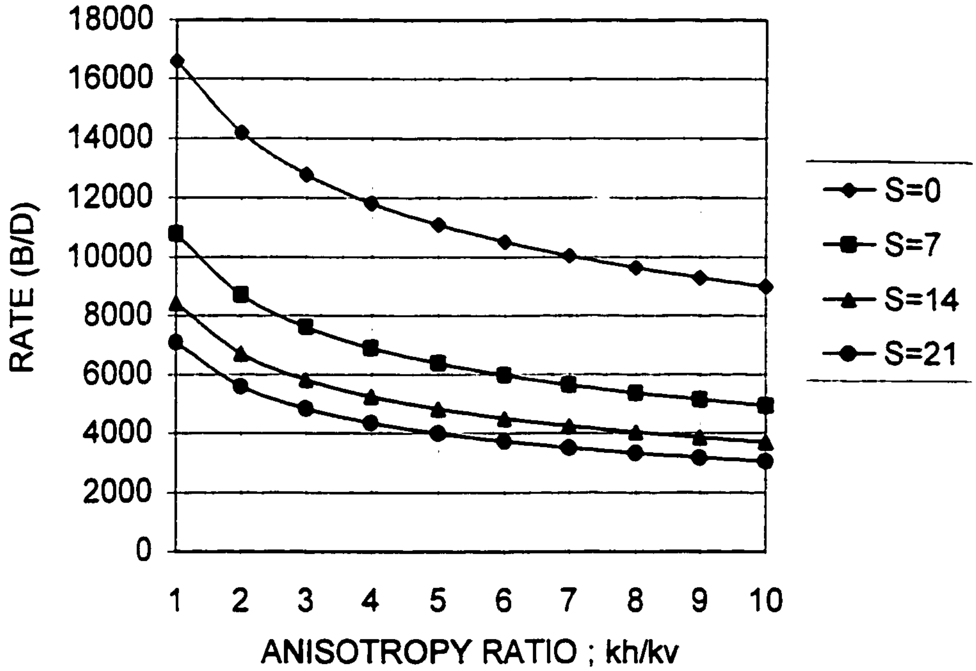

Figure 8-39: Effect of Anisotropy with varying damage for Case-2 profile with LD=0.25 and HD=0.02

In order to investigate the influence of well length on anisotropy, similar experiment is repeated for LD=0.5. As can be seen in Figure 8-40 that variation in the reservoir anisotropy influences more the performance below the value of around 4. However as the anisotropy increases (from 4 to 10) the variation in the performance is dampened. Similar effect can be seen in Figure 8-41, where LD=0.75 is used. In this case however the decrease in the well performance is more pronounced when the anisotropy ratio increases from initial value of one till around the value of 4. Generally the degree of damage does not seem to influence the characteristic shapes of the curves apart from the fact that higher degree of damage yields lower performances.

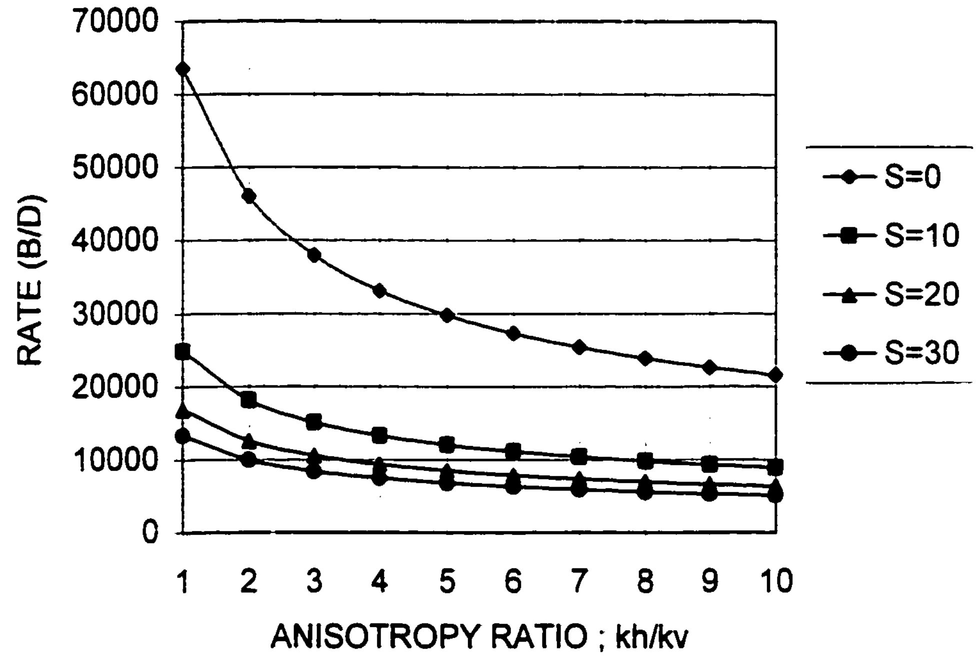

Figure 8-40: Variation of Anisotropy with varying damage for Case-2 profile with LD=0.50 and HD=0.02

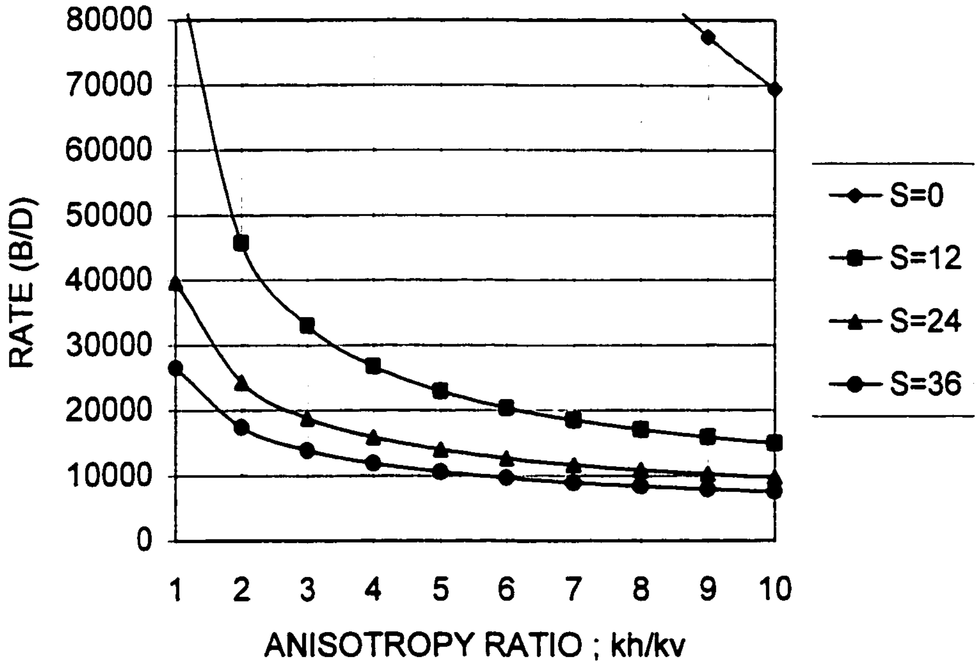

Figure 8-41: Variation of Anisotropy with varying damage for Case-2 profile with LD=0.75 and HD=0.02

The set of experiments performed earlier in this section for case-2 are repeated here for case-3, in order to determine the influence of different skin profiles on the performance of PCHW with variation in the anisotropy.

The data is presented in Table 8-6 and are plotted from Figures 8-42 to 8-44 for LD=0.25 to 0.75 respectively. Apart from the slightly lower well performances there has been no significant deviation in the behavior of the curves as plotted earlier in Figures 8-39 to 8-41 for case-2 profile.

Table 8.6: Horizontal Well Performance (bbls/day) with change in Anisotrpy Ratio for Case-3 Profile

LD=0.25 ; HD=0.02 ; CASE-3				
Kh/Kv	S=0	S=7	S=14	S=21
1	16620	9918	7336	5916
2	14195	7911	5721	4559
3	12795	6864	4908	3888
4	11830	6184	4387	3462
5	11104	5691	4016	3159
6	10528	5312	3731	2929
7	10054	5006	3505	2746
8	9654	4754	3318	2596
9	9310	4540	3160	2470
10	9009	4355	3025	2361
LD=0.50 ; HD=0.02 ; CASE-3				
Kh/Kv	S=0	S=10	S=20	S=30
1	63642	22087	14055	10553
2	46077	16016	10298	7763
3	37989	13300	8590	6483
4	33123	11667	7552	5701
5	29795	10544	6833	5159
6	27340	9709	6296	4752
7	25434	9056	5874	4433
8	23899	8526	5531	4173
9	22628	8085	5245	3956
10	21556	7710	5001	3771
LD=0.75 ; HD=0.02 ; CASE-3				
Kh/Kv	S=0	S=12	S=24	S=36
1	-	64861	27675	17886
2	-	35083	17440	11932
3	-	25859	13686	9578
4	-	21211	11628	8238
5	-	18347	10289	7346
6	-	16375	9331	6698
7	-	14918	8603	6198
8	-	13789	8024	5799
9	-	12882	7551	5469
10	-	12133	7155	5192

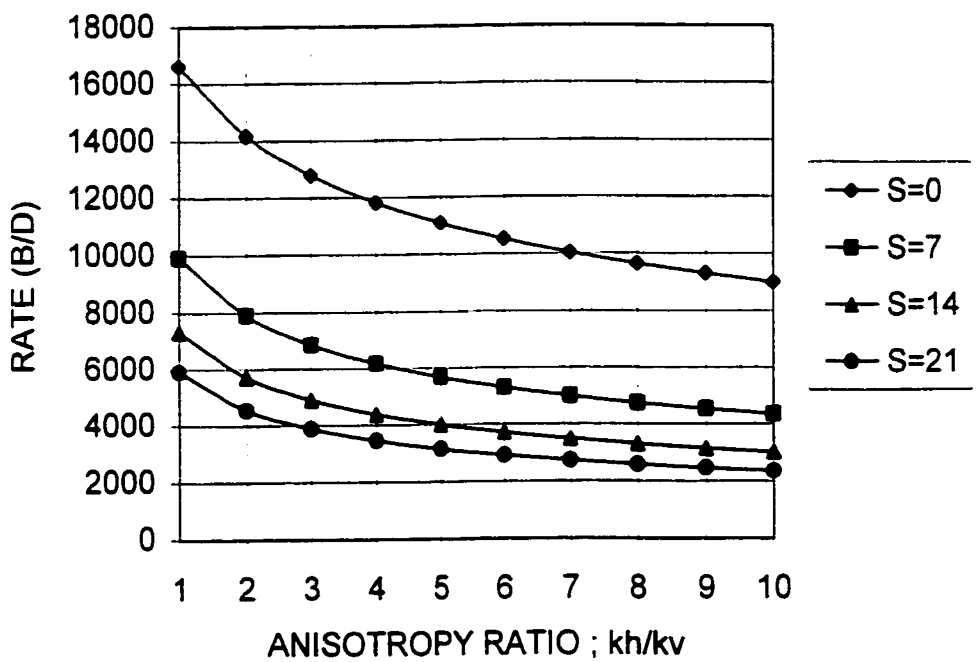

Figure 8-42: Variation of Anisotropy with varying damage for Case-3 profile with LD=0.25 and HD=0.02

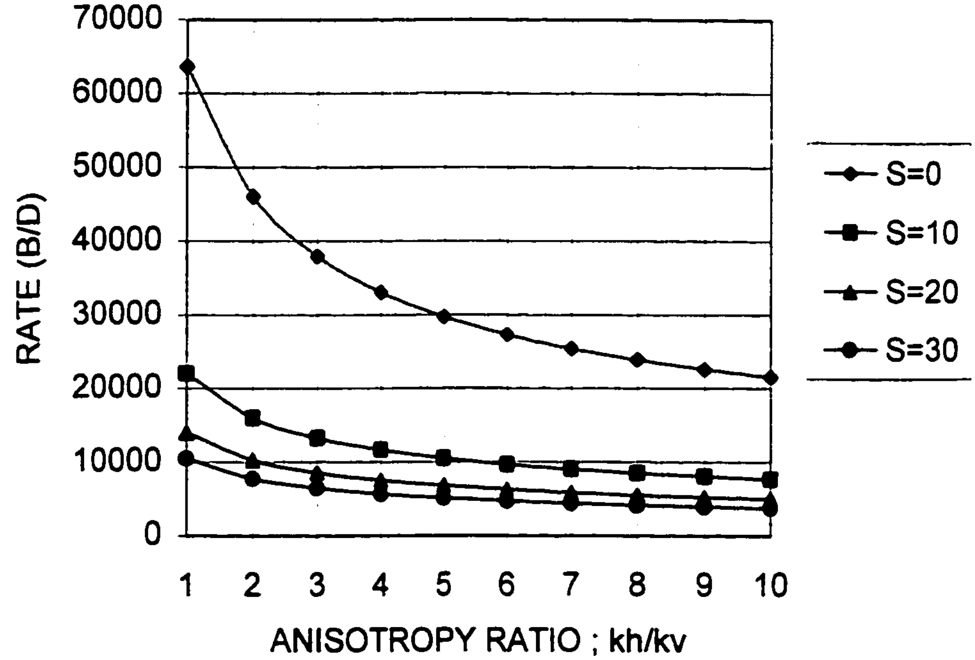

Figure 8-43: Variation of Anisotropy with varying damage for Case-3 profile with LD=0.50 and HD=0.02

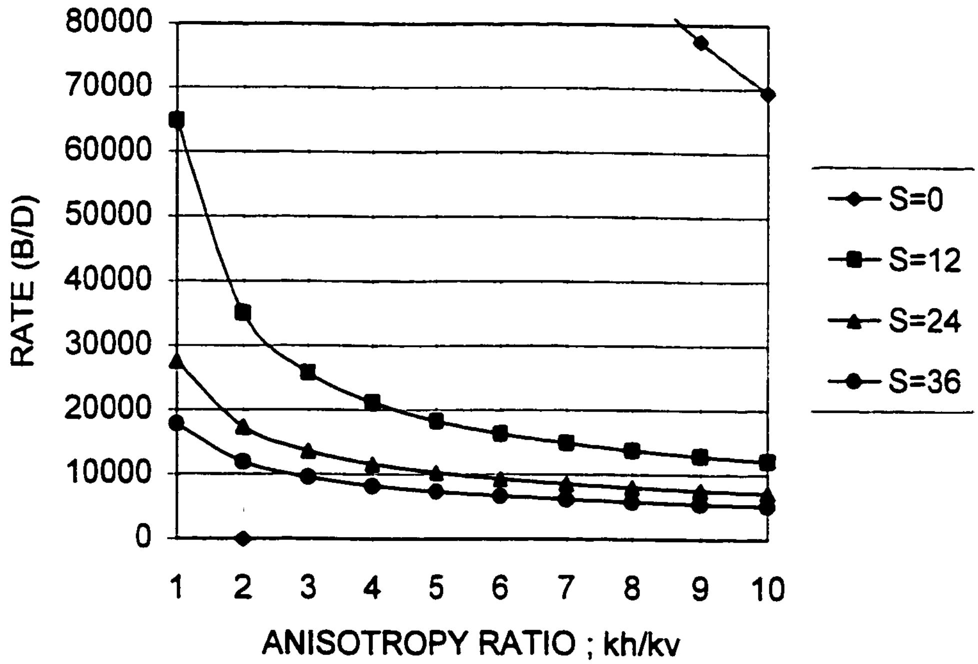

Figure 8-44: Variation of Anisotropy with varying damage for Case-3 profile with LD=0.75 and HD=0.02

8.6.2 Effect of Reservoir Height on Anisotropy change

In this section we want to contemplate the effect of reservoir height on the anisotropy change and subsequently the performance of PCHW. Effect of different levels of skin will also be examined.

The data is presented in Table 8-7. With LD=0.25 the well performance is plotted against anisotropy change for HD=0.005, 0.015 and 0.025 in Figures 8-45 to 8-47 respectively.

Figure 8-45 shows the case of thin reservoir and shorter well length (HD=0.005 and LD=0.25). For S=0 the change in the anisotropy does not seem to affect much of the well performance. The decrease in the performance from the isotropic case (kh/kv=1) to the case with kh/kv=10 is around 15%. However as the degree of formation damage is increased the performance is decreased more visibly with the increase in anisotropy. For example for S=21 the well performance decreases to 55% with kh/kv=10 compared with the well performance at kh/kv=1.

As reservoir height is increased to HD=0.015 (Figure 8-46), the influence of anisotropy change on the curve with S=0, becomes almost similar with curves represented by higher levels of skins. The decrease in the performance with the increase in anisotropy is generally higher for all the curves here as compared with the case in Figure 8-45. Generally with the increase in reservoir height the detrimental influence of increase in anisotropy on the well performance is more pronounced. In these cases, curves with higher level of damage also merge closer as compared with the curve with S=0. This reiterates the fact that smaller degree of damage reduces the performance more pronouncedly than the higher degree of damage. See Figure 8-47.

Table 8.7: Horizontal Well Performance (bbls/day) with change in Anisotrpy Ratio, HD and Degrees of Damage for LD=0.25

LD=0.25 ; HD=0.005 ; CASE-3				
Kh/Kv	S=0	S=7	S=14	S=21
1	5129	4234	3637	3205
2	4947	3850	3193	2749
3	4815	3602	2924	2484
4	4709	3417	2733	2300
5	4619	3271	2585	2160
6	4542	3149	2465	2049
7	4472	3045	2365	1957
8	4410	2955	2279	1878
9	4353	2875	2204	1811
10	4301	2804	2139	1751
LD=0.25 ; HD=0.015 ; CASE-3				
Kh/Kv	S=0	S=7	S=14	S=21
1	13313	8636	6582	5392
2	11802	7095	5257	4241
3	10868	6253	4565	3654
4	10197	5690	4113	3276
5	9677	5275	3786	3004
6	9255	4951	3534	2796
7	8901	4688	3331	2629
8	8598	4468	3162	2491
9	8334	4280	3019	2375
10	8100	4117	2896	2274
LD=0.25 ; HD=0.025 ; CASE-3				
Kh/Kv	S=0	S=7	S=14	S=21
1	19521	10882	7878	6284
2	16127	8487	6039	4774
3	14281	7283	5136	4042
4	13050	6515	4567	3583
5	12146	5966	4164	3259
6	11441	5547	3858	3014
7	10869	5213	3616	2821
8	10391	4937	3416	2662
9	9983	4705	3249	2529
10	9630	4506	3106	2415

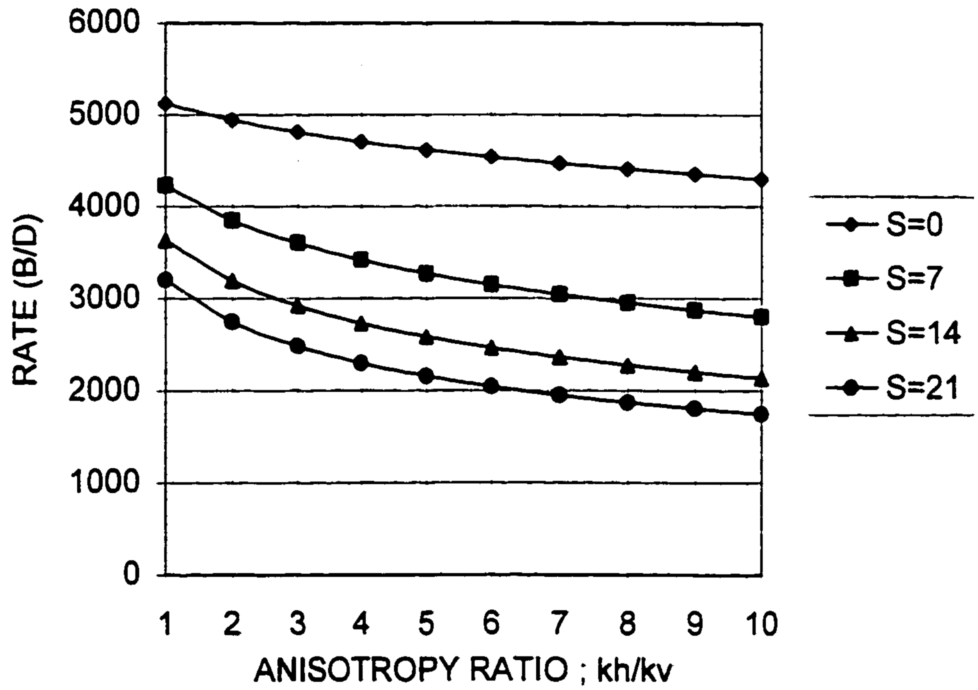

Figure 8-45: Variation of Anisotropy with damage for HD=0.005 and LD=0.25

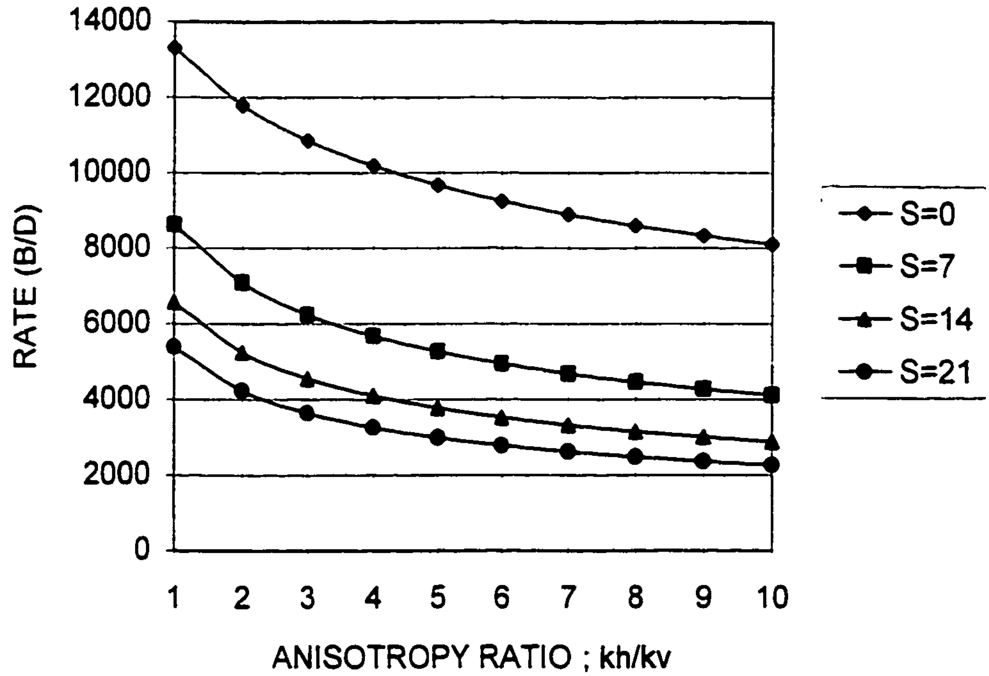

Figure 8-46: Variation of Anisotropy with damage for HD=0.015 and LD=0.25

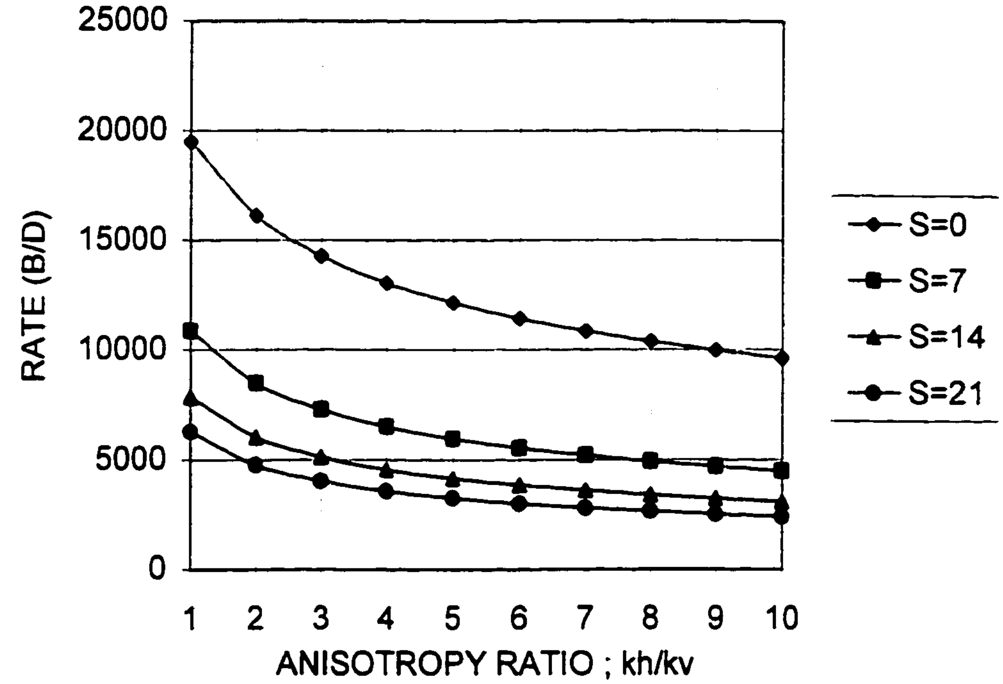

Figure 8-47: Variation of Anisotropy with damage for HD=0.025 and LD=0.25

For the investigation of the effect of increasing well length and anisotropy change on horizontal well performance, the same set of experiments are performed as shown. For LD=0.50, the figures are plotted for HD=0.005,0.015 and 0.025. The data is presented in Table 8-8. Figure 8-48 shows that for S=0, the reduction in the well performance is not rapid with the increase in anisotropy however with the increase in damage and anisotropy the performance reduction is more pronounced. With the increase in reservoir height these effects become more prominent. The performance curve with S=0 is more effected by the anisotropy change and is more salient with the increase in height. However when the higher levels of damage degree is considered, the anisotropy change effect the performance more prominently before and around Kh/Kv=4. apart from the evidently closer performances. See Figures 8-49 and 8-50.

Table 8.8: Horizontal Well Performance (bbls/day) with change in Anisotrpy Ratio, HD and Degrees of Damage for LD=0.50

LD=0.50 ; HD=0.005 ; CASE-3				
Kh/Kv	S=0	S=10	S=20	S=30
1	10598	8165	6721	5752
2	10184	7280	5764	4815
3	9885	6728	5207	4291
4	9645	6327	4819	3935
5	9444	6013	4525	3670
6	9269	5757	4290	3460
7	9115	5541	4095	3289
8	8975	5354	3931	3145
9	8848	5191	3788	3021
10	8732	5046	3663	2913
LD=0.50 : HD=0.015 : CASE-3				
Kh/Kv	S=0	S=10	S=20	S=30
1	40670	18445	12472	9612
2	33036	14110	9454	7253
3	28898	12006	8009	6129
4	26162	10687	7108	5429
5	24168	9756	6473	4937
6	22624	9050	5994	4566
7	21381	8490	5614	4272
8	20349	8030	5302	4031
9	19474	7644	5041	3829
10	18718	7314	4817	3657
LD=0.50 ; HD=0.025 ; CASE-3				
Kh/Kv	S=0	S=10	S=20	S=30
1	93558	25068	15225	11220
2	59680	17413	10876	8104
3	46448	14199	8973	6713
4	39139	12325	7838	5874
5	34410	11061	7061	5297
6	31055	10134	6485	4868
7	28525	9415	6035	4532
8	26536	8837	5671	4259
9	24923	8359	5369	4032
10	23581	7954	5112	3839

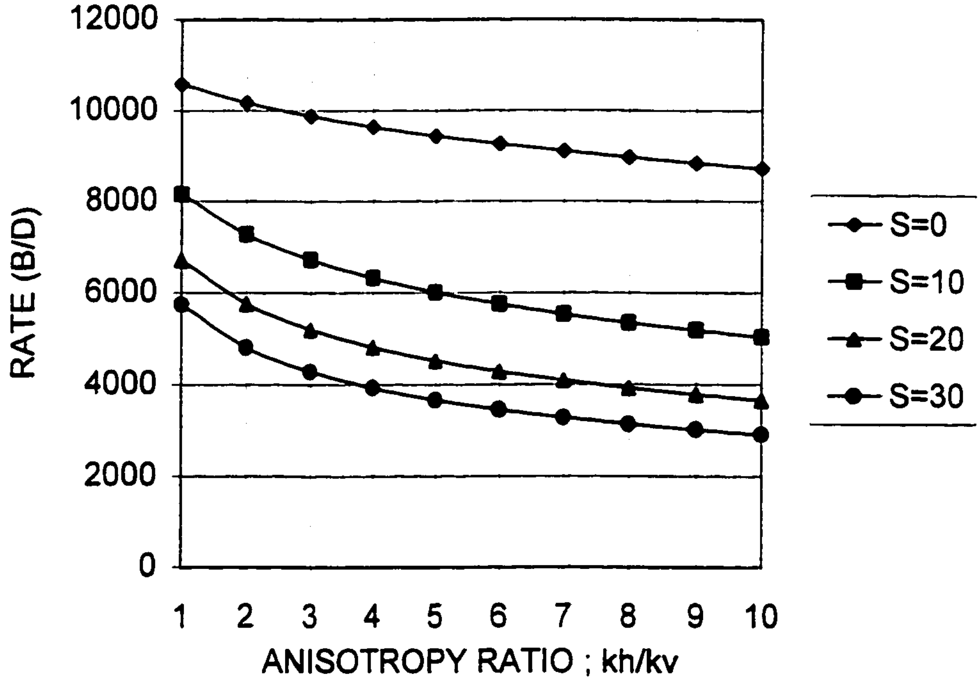

Figure 8-48: Variation of Anisotropy with damage for HD=0.005 and LD=0.50

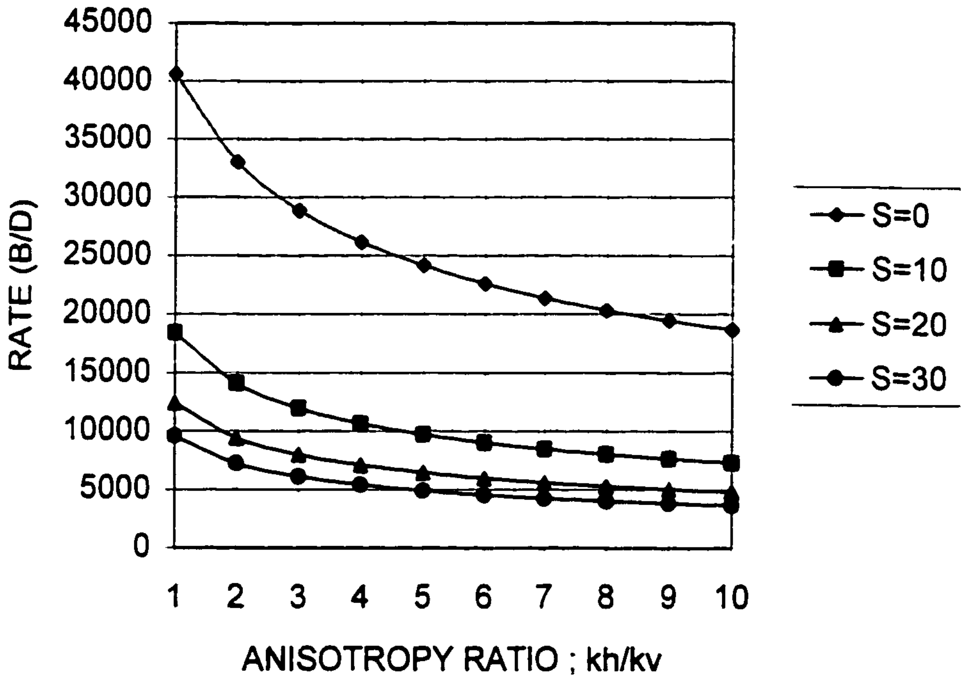

Figure 8-49: Variation of Anisotropy with damage for HD=0.015 and LD=0.50

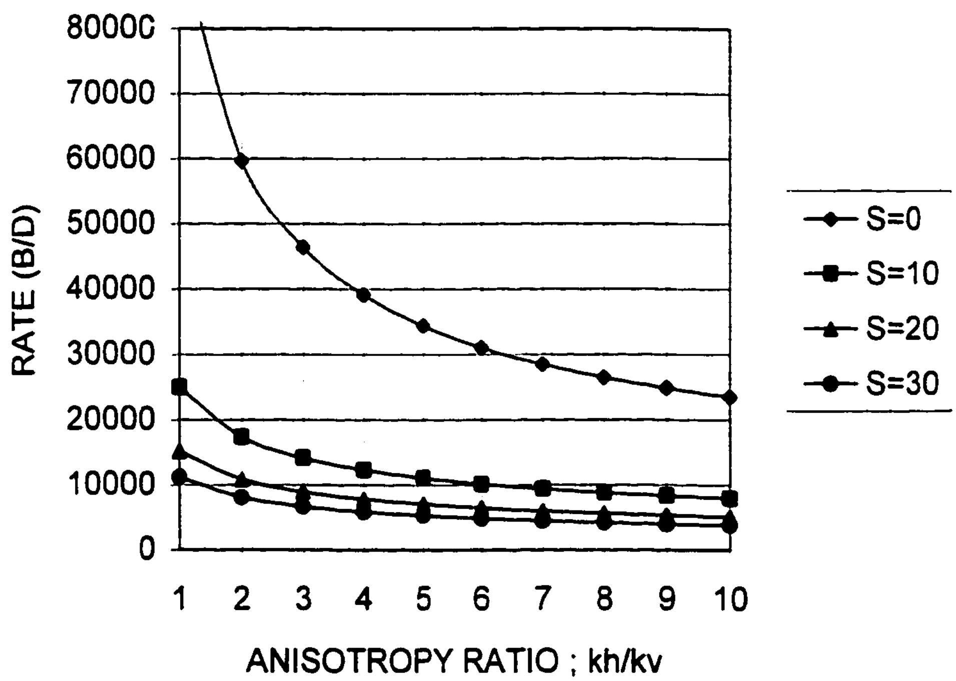

Figure 8-50: Variation of Anisotropy with damage for HD=0.025 and LD=0.50

The sets of experiments done for LD=0.25 and 0.50 are repeated for LD=0.75. The data is presented in Table 8-9 and plotted from Figures 8-51 to 8-53. The same discussion conducted earlier (for LD=0.5) applies for, Figures 8-51 to 53. However the effects and trends are more pronounced in this case.

Finally the following comments can be made:

- As the length increases and, the anisotropy increases, the reduction in the well performance becomes more pronounced.
- With lower degrees of damage, the horizontal well performance is more reduced with the increase in anisotropy ratio, compared when relatively higher degrees of damage are encountered.
- Irrespective of the degree of damage, the reduction is well performance is more evident for initial increase in anisotropy.

Table 8.9: Horizontal Well Performance (bbls/day) with change in Anisotropy Ratio, HD and Degrees of Damage for LD=0.75

LD=0.75 ; HD=0.005 ; CASE-3				
Kh/Kv	S=0	S=12	S=24	S=36
1	24120	15445	11602	9400
2	22559	13055	9455	7516
3	21485	11694	8308	6540
4	20655	10762	7550	5905
5	19975	10064	6995	5445
6	19400	9511	6563	5090
7	18899	9057	6213	4804
8	18458	8674	5921	4567
9	18061	8345	5672	4365
10	17703	8057	5456	4191
LD=0.75 ; HD=0.015 ; CASE-3				
Kh/Kv	S=0	S=12	S=24	S=36
1		48136	23828	16159
2		29556	15909	11178
3		22828	12766	9104
4		19199	10981	7895
5		16871	9795	7079
6		15225	8933	6480
7		13984	8271	6015
8		13007	7742	5641
9		12213	7305	5331
10		11551	6938	5069
LD=0.75 ; HD=0.025 ; CASE-3				
Kh/Kv	S=0	S=12	S=24	S=36
1	-	80838	30632	19120
2	-	39356	18490	12429
3	-	28006	14286	9878
4	-	22565	12036	8450
5	-	19305	10594	7508
6	-	17102	9572	6827
7	-	15497	8800	6306
8	-	14264	8191	5890
9	-	13282	7694	5549
10	-	12476	7279	5261

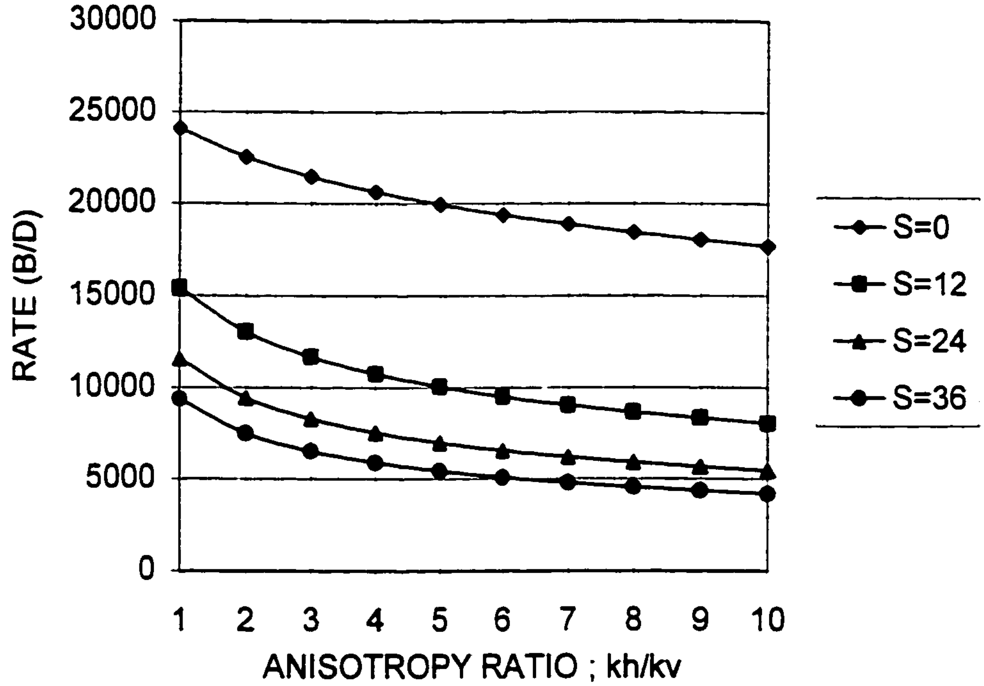

Figure 8-51: Variation of Anisotropy with damage for HD=0.005 and LD=0.75

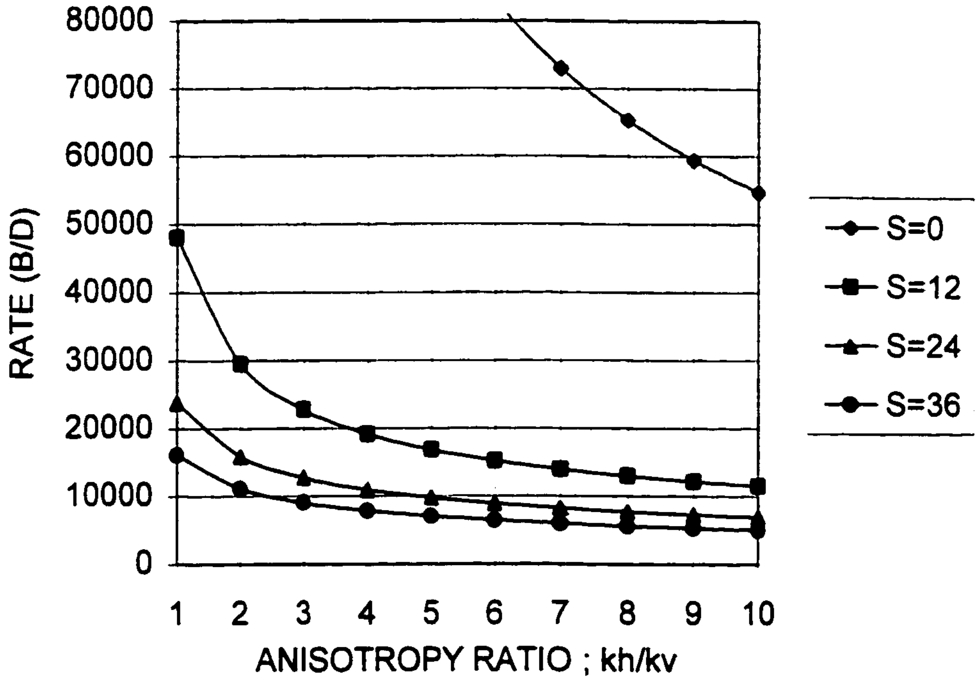

Figure 8-52: Variation of Anisotropy with damage for HD=0.015 and LD=0.75

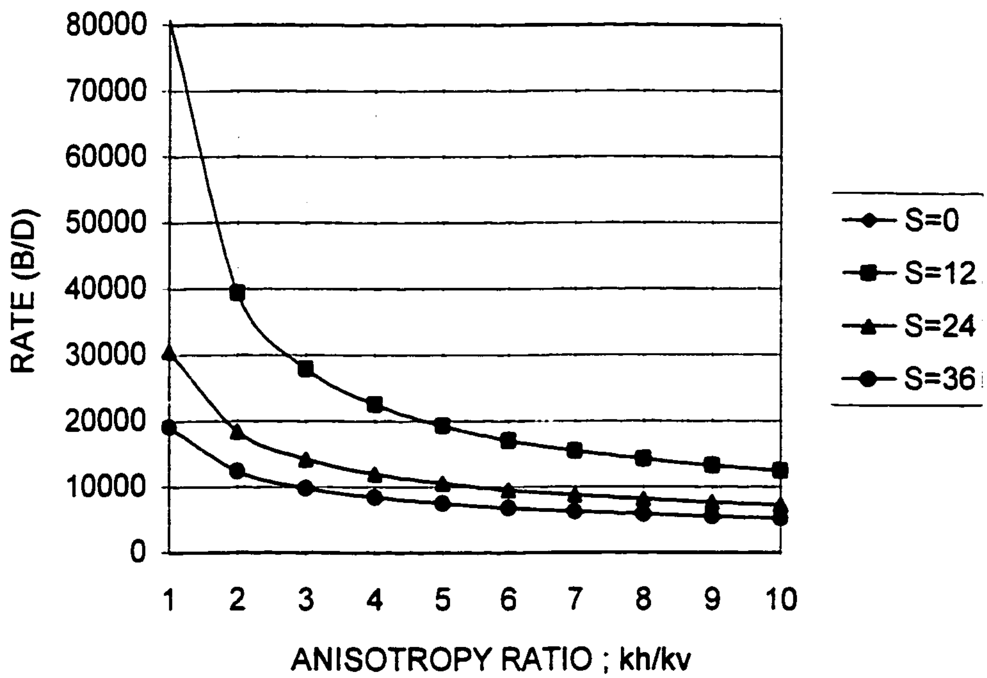

Figure 8-53: Variation of Anisotropy with damage for HD=0.025 and LD=0.75

CHAPTER 9

9. DISCUSSION OF RESULTS

In the previous chapter we have presented the results in the form of parametric study. The results were presented in tabular and graphical forms. Performance of partially completed horizontal wells (PCHW) in presence of formation damage and friction was the center core of discussion. The effect of critical parameters, were evaluated, to see the expected performance of PCHW with especial emphasis on the nature and degree of formation damage. These parameters were; Reservoir Height, Reservoir Anisotropy, Well Length, Well Diameter and Well Open Percentage etc.

The purpose of this chapter is to summarize and examine critically the out come of this study. More specifically, the role of formation damage and friction and their influence on the performance of partially completed horizontal wells will be addressed.

9.1 EFFECT OF DIFFERENT SKIN PROFILE

In the preceding section, the effect of various skin profiles on the flow performance of PCHW was evaluated. It was clearly evident that different skin profiles, with the same average value of the skin, give fairly different performances. The effects were magnified with the increase in well length and reduction in the diameter. The error that may occur in predicting the performance of horizontal wells, when using single value of skin in productivity models is evident if prior knowledge of real distribution of skin or damage is not utilized. These performances improve when the nature of formation damage changes from a constant skin profile to a more steeper one, with higher expected damage at the well heel and lower at the toe.

As can be seen, case-4 (which represents steeper decreasing skin profile) gave highest performance followed by case-2 and case-3 profiles. The case-1, which represented the constant skin profile gave lowest well performance. The synergy of both, distribution of formation damage and role of friction on the influx profile is of consideration here. With lower damages, more flux entered near the toe end. This allows higher frictional pressure loss, as the large mass of flux has to travel a longer distance in the wellbore and it drags more and more influx from the reservoir. As expected these effects are more pronounced with case-4 profile. Case-1 and case-3 perform closely because both represent, near constant damage along the well bore. In these cases, the general impairment in the productivity along the well is almost constant. The influx is evenly distributed along the well, resulted in the lower frictional losses as well, and hence lesser performance than case-2 and case-4 profiles.

9.2 WELL PERFORMANCE AFTER STIMULATION

The results presented earlier revealed that, even lower values of damage significantly reduce well performance. This can be seen through Figures 8.17 to 8.19. The effects are more pronounced with higher frictional loss in the well.

Further, depending on the nature and distribution of damage profile, either stimulation near the heel is beneficial or stimulation near the toe can enhance performance. This is evident in Figures 8.20 to 8.23.

9.3 EFFECT OF RESERVOIR HEIGHT AND WELL LENGTH WITH VARIOUS DEGREES OF DAMAGE

As can be seen in sections, 8.4 and 8.5, that both reservoir height and well length are important parameters when performance of partially completed horizontal well (PCHW) is to be reviewed. For thin reservoirs and shorter well lengths, the loss of production due to restricted perforated length is not significant. We have evaluated the performance of PCHW with especial attention being paid to the degree of formation damage, role of friction forces and the effect of percentage of length open to production.

For thin reservoirs and shorter well lengths higher degree of damage curtail the well performance, however with the increase in reservoir height, the performance of PCHW was more affected by the decrease in the well open percentage. In these cases, the performance of wells is more effected for lower levels of skins, than higher skins values.

This shows that high productivity horizontal wells are more effected by the lower degree of damage.

With larger well lengths and reservoir heights, the usefulness of PCHW when compared with openhole, comes in question. In these cases, a reduction in the well open percentage significantly reduces the performance of PCHW when compared with openhole. In these cases the degree of formation damage becomes more critical and even lower degrees of formation damage can significantly reduce the well performance. Hence in general wells exhibiting higher productivies are more sensitive to formation damage than well with expected lower productivities.

9.4 EFFECT OF RESERVOIR ANISOTROPY ON PERFORMANCE OF PCHW

In section 8.6 the effect of reduction in the anisotropy ratio, represented by kh/kv, on the performance of PCHW was evaluated.

In general the effect of reduction on the well performance is more, evident with the initial increase in reservoir anisotropy.

For shorter wells in comparatively thin reservoirs, the effect of increase in anisotropy does not momentously effect the performance of the well that has no damage. However with the increase in the degree of damage the effect of anisotropy becomes important. The reduction in well performance is more pronounced at the initial increase in anisotropy.

With wells exhibiting higher productivities (larger lengths and thicker reservoir), the increase in anisotropy, curtail the well performance more significantly at lower degrees of damages. Here also the effects are more visible near the initial increase in the anisotropy.

CHAPTER 10

10. CONCLUSION AND RECOMMENDATIONS

10.1 CONCLUSION

This study harnessed the role played by formation damage and friction forces on the flow performance of partially completed horizontal wells. The aftereffect of other important parameters, like well length, diameter, open fraction, reservoir height and anisotropy have also been evaluated. The results are in conformance with the published work in the petroleum literature. However because of the approach employed and detailed study performed here, few important observations can be fashioned:

- A good characterization of the skin profile along the horizontal well is necessary in order to calculate accurately the performance of horizontal wells. If instead of the actual skin profile along the horizontal length, a constant value of the skin is used, the error in calculating the well performance may be significant. Some examples of calculation showed up to 80% error.

- The more important the friction forces in the horizontal well bore, the more significant the deviation between constant and non constant skin profiles, even in the case of the same average value of skin.

- The reduction in horizontal well performance is more significant at lower degrees of damage. In case of partial stimulation, complete removal is essential to restore higher well potentials.

- Horizontal wells exhibiting higher well productivities are more prone to performance reduction by the lower degrees of formation damage.

- Detrimental effect of the increase in anisotropy is more pronounced with higher degrees of damage in thin reservoirs having shorter well lengths. However as reservoir height and well length grows this effect is more salient with the lower degrees of damage.

10.2 RECOMENDATION

The skin profiles used in this study were solely based on theoretical backgrounds. A good characterization of a real skin profile from a filed case is recommended, in order to evaluate the performance of horizontal wells.

The coupling of horizontal well bore, with a multiphase inflow performance for partially completed horizontal wells, is also recommended.

NOMENCLATURE

A	Anisotropy ratio (kh/kv)
B	Formation Volume factor, RB/STB
D	Well diameter, ft.
GF	Geometric factor in productivity model
GOR	Gas/Oil ratio MSCF/STB
h	Reservoir Height, ft,
h_D	Reservoir dimensionless Height
J	Productivity Index (STB/day/psi)
k	Reservoir Permeability, md.
k_s	Skin zone or damaged zone permeability (k_D), md.
k_x	Permeability in x-direction, md.
k_y	Permeability in y-direction, md.
k_z	Permeability in z-direction, md.
k_h	Effective horizontal permeability $=\sqrt{k_x k_y}$, md.
L_x	Reservoir Length, ft.
L_y	Reservoir width, ft.
L_w	Well Length, ft.
LD	Reservoir dimensionless length
L_p	Length of open segment, ft.
L_{pt}	Total length of open segment, ft.

n No. of open segments.

NPI Normalized productivity Index.

PCHW Partially completed horizontal well

p Pressure, psi.

p_{wf} Well flowing pressure

p_{res} Reservoir pressure

p_{ID} Dimensionless inflow pressure

Q Flow rate, bbl/day.

QD Dimensionless flow rate

r_s Damaged radius (r_d), ft

r_w Well radius, ft.

r_e Reservoir external radius. ft.

S Skin factor

S_h Horizontal well skin factor

S_v Vertical well skin factor

S_p Perforation skin

S_{do} Damage skin

X_f Effective horizontal well length

Greek

β Anisotropy ratio = $\sqrt{k_h / k_v}$

μ Viscosity, cp.

θ Angle, degrees

REFERENCES

1. S.D.Joshi & W.Ding : 'Horizontal well application-Reservoir Management'. ' 2nd Inter. Confer. & Exhibit. On Horizontal Well Tech., Calgary, 18-20 Nov'1996

2. S.V.Robertshaw & S.C.Peach : 'Well illustrates challenges of horizontal production logging'. Oil and Gas journal, June 15, 1992

3. Van Everdingen : 'The skin effect and its influence on the productive capacity of a well.' Petroleum transaction, AIME vol. 198, 1953

4. William Hurst : 'Establishment of the skin effect and its impediment to fluid flow into a well bore.' The Petroleum Engineer ; October' 1953

5. M.F.Hawkins : 'A note on the skin Effect'. Petroleum tran., AIME vol. 207, 1956

6. Sparlin,D.D. & Hagen, Jr. : 'Author's reply determining the productivity of horizontal completions,' World oil, pp. 55-61, December 1989

7. Mauduit, D : 'Determining the productivity of horizontal completions,' World oil, pp. 55-61, December 1989

8. Peterson, Merietta & Holditch : 'The effect of skin damage upon the productivity of a well containing a horizontal well bore' SPE formation damage and control Symposium. Lafayette, Feb. 22-23, 1990

9. S.D.Joshi : 'Horizontal well technology'. Pennwell Publishing company, 1991

10. T.P.Frick & M.J.Economides, SPE, Mining U. Leobnan : 'Horizontal well damage characterization and removal'. SPE Production & Facilities, February'1993.

11. G.Renard & J.M.Dupuy : 'Formation damage effects on horizontal-well flow efficiency'. JPT, July, 1991.

12. J.R.Gilman : 'Discussion of formation damage effects on horizontal-well flow efficiency'. JPT, July, 1991.

13. M.J.Economides & C.A.Ehlig-Economides : 'Discussion of formation damage effects on horizontal-well flow efficiency'. JPT Dec.1991

14. J.K.Puncknell ; P.J.Clifford : 'Calculation of total Skin Factors'. Offshore European Conference ; Aberdeen : 3-6 Sept. 1991. (SPE 23100)

15. D.Malekzadeh & D.Tiab, U of Oklahama : 'A new technique for the calculation of mechanical skin damage of horizontal wells caused by drilling fluids.' SPE int. symposium on formation damage and control, Louisiana Feb. 26-27. 1992.

16. D.Malekzadeh ; A.S.Abdelgawad & J.J.Day : 'Quantifying Skin Damage and Improvement in Horizontal wells'. SPE Permian Basin Oil & Gas recovery confer. Texas, 16-18 March'1994.

17. Bob B., Conoco, Houston :'Estimation of formation damage effects on horizontal wells.' Petroleum Engineer Inter. August,1995

18. W.Engler, S.Osisanya and D.Tiab. U. : 'Measuring skin while drilling'. Production operation symposium held in Oklahoma City. 2-4 April' 1995.

19. S.B.Toulekima, D.D.Mamora, R.A.Wattenbarger : 'The effect of skin location, production interval and permeability on performance of horizontal wells' J. of petroleum science and engineering 17(1997) 63-69

20. J.Yan ; G.Jiang & X.Wu : 'Evaluation of formation damage caused by drilling and completion Fluid in Hor. wells'. JCPT May 1997. Volume 36.

21. E.O.Ozkan & R.Raghvan : 'Estimation of Formation Damage in Horizontal Wells'. SPE Production Operations symposium, held in Oklahoma 9-11 March 1997.

22. Roland F.Krueger : 'An Overview of Formation Damage and well productivity in Oil Field Operations.' JPT, Feb.1986

23. D.B.Bennion : F.B.Thomas & D.W.Bennion : 'Effective laboratory coreflood tests to evaluate and minimize formation damage in horizontal wells.' 3rd Inter. Confer. on horizontal well tech. Nov. 12-14, 1991, Houston Texas.

24. A.M.Ezzat, Saudi Aramco : 'Horizontal Drilling and completion fluid design criteria.' SPE Middle East Oil tech. Confer. & Exhibition; Bahrain, 3-6 April 1993.

25. T.Beatty, D.B.Bennion, B. Hebner & R.Hiscock : 'Minimizing formation damage in horizontal wells: Laboratory and field case studies.' CIM 1993, Annual technical conference in Calgary, 1993.

26. D.B.Bennion & D.W.Bennion : 'Fluid design to minimize invasion damage in horizontal wells.' SPE/CIM/CANMET Inter. Confer. On Recent Advances in Horizontal Well Application, March 20-23, 1994, Calgary Canada.

27. N.G.Gruber & K.L.Adair : 'New laboratory procedure for evaluation of drilling induced formation damage and horizontal well performance. JCPT, May'1995 Vol.34

28. J.Yan, G.Jiang & F.Wang. : 'Characterization and Prevention of formation damage during horizontal drilling.' ' 2nd Inter. Confer. & Exhibit. On Horizontal Well Tech. Nov. 18-20 1996- Calgary, Canada. (SPE 37123)

29. J.C.Shaw & T.Chee : 'Laboratory evaluation of drilling mud systems for formation damage prevention in Horizontal wells.' ' 2nd Inter. Confer. & Exhibit. On Horizontal Well Tech. 1996- Calgary, Canada. (SPE 37121)

30. R.M.Hodge, B.G.Augustine, W.W.Sanders and D.J.Atkinson : 'Evaluation and selection of Drill-in fluid Candidates to minimize formation damage.' SPE formation damage and control symposium, Lafayette, Louisiana, USA Feb.1996

31. S.T.Saleh, R.Rustam, W.El-Rabaa and M.R.Islam : 'Formation damage study with a horizontal wellbore model.' J. of petroleum science and engineering 17(1997) 87

32. B.Thomas, M.M.Sharma : 'Distribution of mud induced damage around horizontal wellbores. ' SPE formation damage and control symposium, Lafayette, Louisiana. Feb'1998

33. P.A.Goode & D.J.Wilkinson : 'Inflow Performance of Partially open horizontal wells.' SPE(19341) Eastern regional meeting held in Morgantown, West Virginia, Oct.24-27, 1989 ; (JPT August'1991)

34. Pudji Permadi, Institute Teknologi Bandung : 'Effects of completion scenarios and formation damage on two-phase inflow performance of a horizontal well. SPE formation damage and control symposium, Louisiana USA 14-115 Feb.1996.

35. H.D.Beggs & J.P.Brill : 'A study of two-phase flow in inclined pipes.' JPT, May'1973

36. M.J.Economides ; A.D.Hill & C.Ehlig-Economides : 'Petroleum Production Systems'. Prentice Hall petroleum engineering series ; 1994

37. Five Authors : 'Experts share views on formation damage solutions'. JPT Nov. 1994

38. D.Brant, F.Brent & Ronald Bietz. Hycal : 'Formation damage and Horizontal wells- A Productivity killer.' 2nd Inter. Confer. & Exhibit. On Horizontal Well Tech. Nov. 18-20 1996- Calgary, Canada. (SPE 37138)

39. S.D.Joshi : 'Augmentation of well productivity with slant and horizontal wells'. JPT, June'1988

40. T.G.Byrom and G.R.Coulter : 'Some mechanical aspects of formation damage and removal in horizontal wells'. SPE formation damage and control symposium, Louisiana, USA 14-15 Feb.1996

41. T.Unneland & L.Larsen : 'Limitation of skin concept and its impact on success criteria used in sand control'. European formation damage Confer. Hague, Netherlands, May'1995.

42. T.Unneland & L.Larsen, Statoil : 'Limitation of skin concept and its impact on success criteria used in sand control.' European formation damage conference; Hague, Netherlands 15-16 May, 1995.

43. D.Malekzadeh, M.M.Rahman & J.J.Day : 'Formation Damage Assessment around horizontal wells during injection processes.' ' SPE formation damage and control symposium. LA, USA Feb. 1995.

44. Bennion & F.B.Thomas: 'Recent investigations in formation damage in horizontal wells during overbalance and underbalanced drilling and completion procedures.' Confer. June 1-3 1994, Aberdeen, Scotland.

45. A.M.Ezzat, Baroid : 'Completion fluids design criteria and current technology weakness.' ' SPE formation damage and control symposium, Louisiana, Feb. 22-23, 1990

46. H.Asheim & Piet Oudeman : 'Determination of perforation schemes to control production and injection profiles along horizontal wells.' SPE Drilling and Completion, March'1997

47. H.Yuan, C.Sarica & J.P.Brill : 'Effect of perforation density on single phase liquid flow behavior in horizontal wells.' 2nd Inter. Confer. & Exhibit. On Horizontal Well Tech. Nov. 18-20 1996- Calgary, Canada.

48. M.J.Landman : 'Analytical modeling of selectively perforated horizontal wells.' J. of Pet. Science and engineering. 10(1994) 179-188

49. Karakas and Tariq, Schlumberger : 'Semianalytical productivity models for perforated completions.' (SPE 18247). 63rd annual technical conference and exhibition of SPE ; TX, oct.2-5, 1988

50. K.Brekke & S.C.Lien : 'New, simple completion methods for horizontal wells improve production performance in high-permeability thin zones.' SPE drilling and completion. Sep' 1994

51. V.R.Penmatcha, S.Arbabi & K.Aziz : 'Effects of Pressure drop in Horizontal wells and optimum well length.' SPE Production operations symposium ; Oklahoma, 9-11 March, 1997

52. C.G.Popa & F.C.Simion : 'A new completion technology to improve horizontal well performances.' 2nd Inter. Confer. & Exhibit. on horizontal well tech. Nov. 18-20 1996- Calgary, Canada. (SPE 37111)

53. Masaru Ihara, K Yanai and S.Takao : 'Two phase flow in horizontal wells.' SPE production and facilities, November' 1995

54. K.Seines. I.Aavatsmark, S.C.Lien & Philip Rushworth : 'Considering wellbore friction effects in planning horizontal wells'. JPT, October' 1993.

55. R.A.Novey : 'Pressure drop in horizontal wells: Can they be ignored?' 67th ATC&E of SPE, Washington. DC, October' 1992

56. M.Ihara and N.Shimizu : 'Effect of acceleration pressure drop in a horizontal wellbore.' Tech. Research center. Japan national oil corporation. (1992)

57. K.Suzuki : 'Influence of wellbore hydraulics on horizontal well pressure transient behaviour.' Japan oil development Co., Ltd. (1991)

58. B.J.Dikken : 'Pressure drop in horizontal wells and its effect on production performance.' JPT: November'1990.

59. A.Retnanto. M.J.Economides, C.A.Ehlig-Economides & T.P.Frick : 'Optimization of the performance of Partially completed Horizonal Wells.' SPE Production operations symposium : Oklahoma, 9-11 March, 1997

60. Kuchuk: Goode: Brice & Thambynayagam : 'Pressure Transient Analysis and inflow performance for horizontal wells.' 63rd annual tech. Conference and exhibition of SPE, TX. Oct.2-5. 1988 ; (JPT Aug' 1990)

61. Habib Menouar, AbdulAziz Al-Majid and Syed Sajid Hasan : 'Effect of Non-Uniform Damage on the Inflow Performance of Horizontal Wells.' 1999 SPE Middle East Oil Show Conference –Bahrain, 20-23 February.

APPENDIX A

Inflow Performance frequently expressed by Productivity Index is given as:

$$J = \frac{0.00708 k_{He} h}{\mu B_o \left(P_{ID} + S_m^{*}\right)}$$

where:

$$S_m^{*} = \frac{h}{2L_r}\sqrt{\frac{k_x}{k_z}}\left(S_m\right.$$

The dimensionless inflow pressure P_{ID} can be expressed as sum of two pressure drops: P_{xyD}-called *2-D* fracture contribution and S_{zD} -called *3-D* well contribution.

The first part P_{xyD} is the dimensionless pressure in the *x-y* plane, resulting from treating the well as a set of fracture fully penetrating the formation:

$$P_{xyD} = \frac{\pi L_y}{L_x}\sqrt{\frac{k_x}{k_y}}\left(\frac{1}{3} - \frac{y_w}{L_y} + \frac{y^2{}_w}{L^2{}_y}\right) + \frac{2L_x^2}{\pi^2 L_p^2}\sum_{n=1}^{\infty}\frac{Z_n}{n^3}\left(\sum_{i=1}^{n_p}\cos\frac{n\pi x_i}{L_x} \times \sin\frac{n\pi L_i}{L_x}\right)$$

where:

$$Z_n = \left[1 - \exp\left(-2\alpha_n L_y\right) + \exp\left(-2\alpha_n y_w\right) + \exp\left\{-2\alpha_n\left(L_y - y_w\right)\right\}\right] / \left[1 - \exp\left(-2\alpha_n L_y\right)\right)$$

here:

$$\alpha_n = \frac{n\pi}{L_z}\sqrt{\frac{k_x}{k_z}} \text{ and } L_p = \sum_{i=1}^{n_p} L_i$$

The second part S_{zD} is an additional skin that results because the well does not fully penetrate the formation and the flow must converge near the well:

$$S_{zD} = \frac{h}{2L_p}\sqrt{\frac{k_x}{k_z}}\left[-\ln\left(\frac{2\pi r_w'}{h}\sin\frac{\pi z_w}{h}\right) - \frac{n_p h}{L_p}\sqrt{\frac{k_x}{k_z}}\left(\frac{1}{3} - \frac{z_w}{h} + \frac{z_w^2}{h^2}\right)\right] + 2\sum_{k=1}^{\infty} F_w^*(\beta)\cos^2\frac{k\pi z_w}{h}$$

where:

$r_w' = \frac{1}{2}\left(1 + \sqrt{\frac{k_z}{k_x}}\right) r_w$; $\beta = \frac{\pi^2 k^2}{h^2}\frac{k_z}{k_x}$ and the function $F_w^*(\beta)$ is defined as:

$$F_w^*(\beta) = \frac{E}{L_p}\int_{\sqrt{\beta}}^{\infty}\frac{du}{\sqrt{u^2-\beta}}\frac{1}{2u^2}\sum_{i=1}^{n_p}\left[\exp(-2uL_i + 4\sum_{j<i}\exp\left(-u|x_j - x_i|\right)\times \sinh uL_i \sinh uL_j\right]$$

Transformation of Variable

This is accomplished to transform the infinite integral as used in the definition of $F_w^*(\beta)$ into finite one. The transformation is done to achieve faster convergence of the function in the computer modeling of the inflow performance. Assuming. $u = \sqrt{\beta}\sec\theta$ in $F_w^*(\beta)$. Then after transformation of variable, $F_w^*(\beta)$ can be written in the form of, $F_w^*(\theta)$ as:

$$F_w^*(\theta) = \frac{1}{2\beta L_p^2} \int_0^{\pi/2} \cos\theta d\theta \sum_{i=1}^{n_p} [\exp(-2\sqrt{\beta}\sec\theta L_i) + 4\sum_{j<i} \exp\left(-\sqrt{\beta}\sec\theta |x_j - x_i|\right) \times$$

$$\sinh(\sqrt{\beta}\sec\theta L_i) \times \sinh(\sqrt{\beta}\sec\theta L_j)]$$

APPENDIX B

One of the sample out put obtained from the simulated run is shown as below:

```
*********************************************************************************
------------------- HORIZONTAL WELL HYDRAULICS / PRODUCTION ------------------
*********************************************************************************

Prod.Index: (STB D/psi)   =  820.31
Oil gravity  ( API )      =  30.00
RSi: (scf/STB)            =  400.00
Hor. well length (ft)     = 2000.00
Open percent of wellbore  =  50.00
No. of open intervals     =  5
Reservoir temperature (F) =  160.00
Reservoir pressure (Psig) = 2250.00
Pressure @ welltoe (Psig) = 2200.00

****************PRESSURE DROP CALCULATIONS ALONG WELL*****************
*********************************************************************************
```

SEG.	TYPE	LOC(Xi)	PRESSURE	DP	RATE	Qo/QM	REGIME	Rso	Bo	DENM	VISM
5	PERF	1980.00	2200.0	.00	727.72	1.00	1-PHASE	400.00	1.227	48.52	1.13
5	PERF	1960.00	2200.0	.00	1340.69	1.00	1-PHASE	400.00	1.227	48.52	1.13
5	PERF	1940.00	2200.0	.00	1884.16	1.00	1-PHASE	400.00	1.227	48.52	1.13
5	PERF	1920.00	2200.0	-.01	2380.31	1.00	1-PHASE	400.00	1.227	48.52	1.13
5	PERF	1900.00	2200.0	-.01	2841.82	1.00	1-PHASE	400.00	1.227	48.52	1.13
5	PERF	1880.00	2200.0	-.01	3276.64	1.00	1-PHASE	400.00	1.227	48.52	1.13
5	PERF	1860.00	2200.0	-.01	3690.14	1.00	1-PHASE	400.00	1.227	48.52	1.13
5	PERF	1840.00	2200.0	-.01	4086.15	1.00	1-PHASE	400.00	1.227	48.52	1.13
5	PERF	1820.00	2199.9	-.02	4467.48	1.00	1-PHASE	400.00	1.227	48.52	1.13
5	PERF	1800.00	2199.9	-.02	4836.29	1.00	1-PHASE	400.00	1.227	48.52	1.13
5	PIPE	1550.00	2199.9	-.24	4836.29	1.00	1-PHASE	400.00	1.227	48.52	1.13
4	PERF	1530.00	2199.7	-.02	5122.81	1.00	1-PHASE	400.00	1.227	48.52	1.13
4	PERF	1510.00	2199.7	-.02	5406.10	1.00	1-PHASE	400.00	1.227	48.52	1.13
4	PERF	1490.00	2199.6	-.03	5686.39	1.00	1-PHASE	400.00	1.227	48.52	1.13
4	PERF	1470.00	2199.6	-.03	5963.84	1.00	1-PHASE	400.00	1.227	48.52	1.13
4	PERF	1450.00	2199.6	-.03	6238.64	1.00	1-PHASE	400.00	1.227	48.52	1.13
4	PERF	1430.00	2199.5	-.03	6510.93	1.00	1-PHASE	400.00	1.227	48.52	1.13
4	PERF	1410.00	2199.5	-.04	6780.86	1.00	1-PHASE	400.00	1.227	48.52	1.13
4	PERF	1390.00	2199.5	-.04	7048.56	1.00	1-PHASE	400.00	1.227	48.52	1.13
4	PERF	1370.00	2199.4	-.04	7314.16	1.00	1-PHASE	400.00	1.227	48.52	1.13
4	PERF	1350.00	2199.4	-.04	7577.78	1.00	1-PHASE	400.00	1.227	48.52	1.13
4	PIPE	1100.00	2199.4	-.55	7577.78	1.00	1-PHASE	400.00	1.227	48.52	1.13

3	PERF	1080.00	2198.8	-.05	7821.69	1.00	1-PHASE	400.00	1.227	48.52 1.13
3	PERF	1060.00	2198.8	-.05	8064.52	1.00	1-PHASE	400.00	1.227	48.52 1.13
3	PERF	1040.00	2198.7	-.05	8306.33	1.00	1-PHASE	400.00	1.227	48.52 1.13
3	PERF	1020.00	2198.7	-.06	8547.16	1.00	1-PHASE	400.00	1.227	48.52 1.13
3	PERF	1000.00	2198.6	-.06	8787.05	1.00	1-PHASE	400.00	1.227	48.52 1.13
3	PERF	980.00	2198.5	-.06	9026.06	1.00	1-PHASE	400.00	1.227	48.52 1.13
3	PERF	960.00	2198.5	-.07	9264.23	1.00	1-PHASE	400.00	1.227	48.52 1.13
3	PERF	940.00	2198.4	-.07	9501.59	1.00	1-PHASE	400.00	1.227	48.52 1.13
3	PERF	920.00	2198.3	-.07	9738.20	1.00	1-PHASE	400.00	1.227	48.52 1.13
3	PERF	900.00	2198.3	-.07	9974.09	1.00	1-PHASE	400.00	1.227	48.52 1.13
3	PIPE	650.00	2198.2	-.94	9974.09	1.00	1-PHASE	400.00	1.227	48.52 1.13
2	PERF	630.00	2197.3	-.08	10202.48	1.00	1-PHASE	400.00	1.227	48.52 1.13
2	PERF	610.00	2197.2	-.08	10430.43	1.00	1-PHASE	400.00	1.227	48.52 1.13
2	PERF	590.00	2197.1	-.09	10657.99	1.00	1-PHASE	400.00	1.227	48.52 1.13
2	PERF	570.00	2197.0	-.09	10885.19	1.00	1-PHASE	400.00	1.227	48.52 1.13
2	PERF	550.00	2196.9	-.09	11112.04	1.00	1-PHASE	400.00	1.227	48.52 1.13
2	PERF	530.00	2196.8	-.10	11338.58	1.00	1-PHASE	400.00	1.227	48.52 1.13
2	PERF	510.00	2196.7	-.10	11564.83	1.00	1-PHASE	400.00	1.227	48.52 1.13
2	PERF	490.00	2196.6	-.10	11790.82	1.00	1-PHASE	400.00	1.227	48.52 1.13
2	PERF	470.00	2196.5	-.11	12016.57	1.00	1-PHASE	400.00	1.227	48.52 1.13
2	PERF	450.00	2196.4	-.11	12242.12	1.00	1-PHASE	400.00	1.227	48.52 1.13
2	PIPE	200.00	2196.3	-1.39	12242.12	1.00	1-PHASE	400.00	1.227	48.52 1.13
1	PERF	180.00	2194.9	-.12	12465.86	1.00	1-PHASE	400.00	1.227	48.52 1.13
1	PERF	160.00	2194.8	-.12	12689.54	1.00	1-PHASE	400.00	1.227	48.52 1.13
1	PERF	140.00	2194.7	-.12	12913.17	1.00	1-PHASE	400.00	1.227	48.52 1.13
1	PERF	120.00	2194.6	-.13	13136.78	1.00	1-PHASE	400.00	1.227	48.52 1.13
1	PERF	100.00	2194.4	-.13	13360.39	1.00	1-PHASE	400.00	1.227	48.52 1.13
1	PERF	80.00	2194.3	-.14	13584.02	1.00	1-PHASE	400.00	1.227	48.52 1.13
1	PERF	60.00	2194.2	-.14	13807.70	1.00	1-PHASE	400.00	1.227	48.52 1.13
1	PERF	40.00	2194.0	-.14	14031.44	1.00	1-PHASE	400.00	1.227	48.52 1.13
1	PERF	20.00	2193.9	-.15	14255.27	1.00	1-PHASE	400.00	1.227	48.52 1.13
1	PERF	.00	2193.7	-.15	14479.22	1.00	1-PHASE	400.00	1.227	48.52 1.13

@ X=0 :
Total flow rate = 14479.2bbl/day
Pressure = 2193.6psig and Temp.= 160.0F
Total pressure drop = 6.42psig

****************************** END OF RESULTS ************************************

VITAE

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